The effect of once-off tillage on selected soil physical and chemical properties and resultant crop response on a shale derived soil under no-till in the Swartland sub-region of the Western Cape

by

Izané Riana Leygonie

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date:……………………………………………..

Abstract

Conservation agriculture is widely adopted by farmers who claim that any soil disturbance will be detrimental to both soil physical and chemical properties. However, as the effect of reduced tillage and maximum stubble retention becomes more prevalent, secondary effects, positive or negative, may develop at soil surface or in the upper layers of the soil profile. Therefore, an increased interest in strategic tillage have arose in order to address the emerging CA constraints. CA can be defined as the avoidance of mechanical soil disturbance combined with the maintenance of a permanent soil cover and the implementation of a crop rotation system. The study formed part of a long-term field trial established in 2007 investigating different crop and crop/pasture systems under no-tillage at the Langgewens Research Farm of the Western Cape Department of Agriculture, near Moorreesburg, Swartland, Western Cape, South Africa. The study was conducted during the 2014 and 2015 growing seasons to assess the effect of once-off tillage (till once in 10 years) in long-term medic/wheat/medic/wheat (McWMcW), wheat/lupin/wheat/canola (WLWC), lupin/wheat/canola/wheat (LWCW), wheat/medic/wheat/medic (WMcWMc) and canola/wheat/lupin/wheat (CWLW) cropping systems (the last letter in the sequence represents the crop that was in field at sampling time). Three once-off tillage treatments namely: continuous no-till (NT, soil left undisturbed until planting and then planted with an Ausplow), deep tine non-inversion tillage (DT) and mouldboard inversion tillage (MP) were conducted. Tillage treatments were conducted on 26 and 27 May, in 2014 and 2015, respectively. NT treatments were regarded as a control reference for this study. In February 2014 and May 2015, soil samples were taken at 0-50, 50-100, 100-200, 200-300 and 300-400 mm depth increments. Soil water content measurements were taken weekly (during growing season) and monthly (during fallow season) to a depth of 800 mm in order to determine the soil water balance and the resultant crop performance.

The objectives of the study were to investigate the effect of once-off tillage of no-till soil on: i) the soil physical and chemical properties, ii) the soil water balance parameters, (iii) and the resultant crop performance (water use efficiency and rainfall use efficiency) as affected by physical, chemical and soil water balance related properties.

Significant differences in particle size distribution between tillage treatments at different depths were found (P = 0.05). Tillage had no significant effect on coarse fragment percentage in both wheat systems investigated in the study (P = 0.05), although, in the canola after wheat system the DT treatment resulted in a significant higher coarse fragment percentage in the 200-300 mm soil depth (P ≤ 0.05). The general

coarse fragment percentage trend observed was an increase with depth. This result is however not indicative of a mechanical sieving action which is usually expected after the repeatable conduction of conventional tillage practices. DT was the only treatment to result in significant aggregate stability decreases in both the WLWC and LWCW crop rotation systems. In the 300-400 mm soil depth (LWCW) a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment (P = 0.1514) while in the 0-100 mm (WLWC) soil depth a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment (P = 0.0078). The aggressive mechanical action of the deep tine implement was responsible for the aggregate stability decrease. Aggregate stability decreased with depth and therefore results correlated with SOC results due to increases in aggregate stability percentages in soil depths where increases in SOC were observed. According to results obtained once-off tillage had no significant effect on macro-aggregate density (P = 0.05) and it was concluded that the sample clods used for measurement were not representative of the prevailing soil conditions after tillage conduction. Hydraulic conductivity showed significant differences between treatments. Although not always significant, both the NT and DT treatments showed the highest hydraulic conductivity compared to MP for all cropping systems investigated (P = 0.05). The increase in hydraulic conductivity for the DT treatment can be explained by a more favourable soil structure created by the rip action, while the increase under NT was contributed to the preservation of soil macro-pores which is formed by earthworms and decayed plant roots as well as the present mulch layer. A MP tillage action leaves a soil surface bare which exposes the soil surface to compacting effects of rainfall and soil resettlement.

MP tillage had a significant effect on pH (KCl and H_2O) while DT tillage had no significant effect. Significant differences were however only observed in the 0-50 mm and 50-100 mm soil depth increments (P = 0.05). The general trend was an increase in pH (KCl and H_2O) with depth and therefore it was concluded that differences were not attributed to a tillage effect but rather to the inherent mother material properties. It is well known that mother materials have higher pH values compared to weathered soil materials. A decreasing trend with soil depth was observed for electrical conductivity. DT proved to be the least favourable in terms of the leaching of salts due to EC increases while NT proved to be the most favourable. The SOC content was not influenced by the single tillage operation as no significant differences were observed between all tillage treatments at all measured depths (P = 0.05). The highest SOC content was observed in the 0-100 mm soil depth where after SOC decreased with each measured depth. The Active C content was not significantly influenced by a once-off tillage operation as was expected in 2014 (P = 0.0005). The prevailing low soil temperatures did not allow active microorganism activity. In 2015 (1 year after tillage) a significant increase in active C content (P = 0.0258) was observed for DT for both the medic after wheat and the wheat after canola systems which was explained by an increase in microbe activity due to favourable soil conditions.

Tillage had a negligible small effect on SWC during the 2014 growing season. Significant differences were only observed between NT and DT after big rainfall events and at the end of the growing season ($P = 0.05$). SWC readings in 2014 ranged between 35-270 mm for all tillage treatments and crop rotation systems measured. ET values varied according to the crops developing stage as well as the available SWC and external environmental factors (rainfall and temperature). Tillage had no significant effect on ET as no significant difference in ΣET was observed at the end of the 2014 growing season ($P = 0.05$). Tillage had no effect on the ability of the soil to store water during the 2014/2015 fallow season as no significant difference in SWC were observed between treatments. More valuable results would have been obtained during the fallow season if technical difficulties could have been solved. The total amount of rainfall recorded during the 2015 growing season was 31% lower compared to rainfall recorded during 2014 and therefore SWC readings during 2015 ranged between 10-140 mm. Generally, the highest SWC was observed for the MP treatment for all crop rotation systems and on several dates significant higher SWC readings were observed for MP compared to NT and DT ($P \leq 0.05$). MP resulted in a significantly higher ΣET at the end of the 2015 growing season ($P = 0.05$). Due to limited information on the topic a valuable explanation for the higher SWC and ΣET under MP was not found.

In the 2014 growing season no significant differences in wheat yield were found between all tillage treatments and crop rotation systems investigated while for the 2015 growing season NT resulted in a significantly higher wheat yield ($P = 0.0274$) compared to both DT and MP in the CWLW system which was attributed to the crop residues present. Although the lowest biomass was obtained for the MP treatment no significant difference between treatments were observed for medics ($P = 0.9010$). The lower biomass under medics was contributed to the transportation of the self-regenerating medic seeds during the inversion plough action which resulted in seedling emergence delays and poor crop stand. When comparing the 2014 and 2015 grain yield results a 71% decrease in canola yield was observed while a 57% decrease in wheat grain yield was observed in the 2015 growing season. Even though the crops underwent a longer growing season during 2015 a total of 31% less rainfall was recorded during the 2015 growing season compared to the 2014 growing season and therefore lower grain yields were expected. Once-off tillage had no significant effect on WUE and RUE in both the 2014 and 2015 growing seasons for all tillage treatments and crop rotation systems tested.

Abstrak

Bewaringsboerdery word wêreldwyd deur boere aangeneem wie vasgestel het dat enige grondversteuring noodlottig is vir beide grondfisiese en grondchemiese eienskappe. Alhoewel, soos wat die effek van verminderde bewerking en maksimum stoppelbehoud meer opvallend raak, kan sekondêre effekte, positief of negatief, ontwikkel by die grondoppervlak of in die boonste grondlae van die grondprofiel. Daarom het 'n toenemende belangstelling in strategiese bewerking na vore gekom om sodoende die bewaringsbewerking beperkings te adresseer. Die studie het deel gevorm van 'n langtermyn proef, gevestig in 2007, wat verskillende gewas/weiding sisteme onder geen bewerking ondersoek by Langgewens Navorsingsplaas van die Departement Landbou Wes-Kaap naby Moorreesburg, Swartland, Suid-Afrika. Die studie is uitgevoer gedurende die 2014 en 2015 groeiseisoen om sodoende die effek van eenmalige bewerking (bewerk eenmalig in 10 jaar) van geen bewerkde grond in langtermyn medic/koring/medic/koring (McKMcK), koring/lupiene/koring/kanola (KLKC) and lupiene/koring/kanola/koring (LKCK), koring/medic/koring/medic (KMcKMc) en kanola/koring/lupiene/koring (CKLK) gewassisteme (die laaste letter in die volgorde verteenwoordig die gewas teenwoordig in die veld by monsterneming). Drie eenmalige bewerkingsbehandelings is uitgevoer naamlik: aanhoudende geen-bewerking (NT, grond onversteur gelaat tot plant en dan word geplant met 'n Ausplow), diep tand geen omkering bewerking (DT) skaarploeg omkeer bewerking (MP). Bewerkings is uitgevoer op 26 en 27 Mei 2014. Geen bewerkings behandelings is geag as kontrole vir die studie. In Februarie 2014 en 2015 is grondmonsters geneem by 0-50, 50-100, 100-200, 200-300 en 300-400 mm diepte inkremente. Grondwaterinhoud metings is weekliks geneem (gedurende groeiseisoen) en maandeliks (gedurende braakseisoen) tot 'n diepte van 800 mm om sodoende die grondwaterbalans te bepaal en die resulterende gewasprestasie.

Die objektiewe van die studie was om die effek van eenmalige bewerking van geen bewerkde grond te ondersoek op: i) die grond fisiese en chemise eienskappe soos geaffekteer deur eenmalige bewerking, ii) die grondwaterbalans soos geaffekteer deur eenmalige bewerking, iii) en die resulterende gewasprestasie (waterverbruiksdoeltreffendheid en reënvalverbruiksdoeltreffendheid) soos geaffekteer deur fisiese, chemiese en grondwaterbalans verwante eienskappe na die uitvoer van eenmalige bewerking.

Betekenisvolle verskille in partikelgrootte verspreiding tussen behandelings is gevind (P = 0.05). Betekenisvolle verskille is mees kenmerklik gevind vir die growwe- en fyn sandfraksie en tussen NT en DT behandelings. Bewerking het geen betekenisvolle effek gehad op growwe fragment persentasie in beide

koring stelsels ($P = 0.05$), alhoewel, DT het geresulteer in betekenisvolle hoër growwe fragment persentasies vergelykend met MP en NT behandelings in die 200-300 mm gronddiepte ($P \leq 0.05$). Die algemene tendens was 'n verhoging in growwe fragment persentasie met diepte. Die tendens was alhoewel nie verteenwoordigend van 'n meganiese siftings aksie wat gewoonlik resulteer na aanhoudende uitvoer van konvensionele bewerkingspraktyke nie. DT het 'n betekenisvolle effek op aggregaatstabiliteit gehad. DT het in 'n betekenisvolle laer aggregaatstabiliteit geresulteer vergelykend met NT in die 300-400 mm gronddiepte in 'n LKCK stelsel ($P = 0.1514$), asook, DT het 'n betekenisvolle laer aggregaatstabiliteit gehad vergelykend met NT in die 0-100 mm diepte vir WLWC ($P = 0.0078$). Aggregaatstabiliteit het verlaag met diepte en daarom korrelleer resultate met grond organiese koolstof (GOK) resultate as gevolg van verhogings in aggregaatstabiliteit persentasies in gronddieptes waar verhogings in GOK opgemerk is. Eenmalige bewerking het geen betekenisvolle effek op makro-aggregaat digtheid gehad nie ($P = 0.05$). Daar was tot die gevolgtrekking gekom dat kluitmonsters nie 'n aanduiding was van die heersende grondkondisies soos na bewerking te verwagte is nie. Hidrouliese geleiding het betekenisvolle verskille tuseen behandelings getoon. Alhoewel nie altyd betekenisvol verskillend nie, het beide NT en DT behandelings die hoogste hidrouliese konduktiwiteit getoon vergelykend met MP vir alle stelsels betrokke ($P = 0.05$). Die verhoging in hidrouliese konduktiwiteit kan toegeskryf word aan 'n meer gunstige grondstruktuur geskep deur die tandaksie, terwyl die verhoging onder NT toegeskryf word aan die preservering van die grond se makroporieë gevorm der erdwurms en verotte plantwortels asook die teenwoordigende restelaag. Die MP bewerking laat die grond naak na bewerking wat die grond blootstel aan partikel hervestiging en konsolidasie onder die invloed van reënval.

MP het 'n betekenisvolle effek op pH (KCl and H_2O) gehad terwyl DT geen betekenisvolle effek getoon het nie. Betekenisvolle verskille is slegs waargeneem in die 0-50 mm en 50-100 mm diepte. Die algemene tendens was 'n verhoging in pH (KCl en H_2O) met diepte en daarvoor is daar tot die gevolgtrekking gekom dat verskille nie toegeskryf is aan bewerking nie maar eerder die teenwoordigende moedermateriaal. Dit is welbekend dat moedermateriale hoër pH's besit as verweerde grondmateriale. 'n Verlagende tendens met gronddiepte is opgemerk vir elektriese konduktiwiteit (EC). DT het bewys om ongunstig te wees ten opsigte van loging van soute as gevolg van EC verhogings terwyl NT die meeste gunstig was vir die doel.
Die GOK inhoud was nie beinvloed deur die enkele bewerkingsoperasie nie omdat geen betekenisvolle verskille met diepte opgemerk is nie ($P = 0.05$). Die hoogste GOK inhoud is gesien in die 0-100 mm gronddiepte waar GOK met elke gemete diepte verlaag het vir alle behandelings. Die aktiewe koolstof inhoud was nie betekenisvol beinvloed deur 'n eenmalige bewerkings operasie nie soos wat te verwagte was in 2014 as gevolg van heersende koue grondtemperature wat mikro organisme aktiwiteit vertraag (P

= 0.0005). In 2015 (1 jaar na bewerking) is 'n betekenisvolle verhoging in aktiewe koolstof opgemerk (P = 0.0258) vir DT in beide medic na koring en koring na canola stelsels as gevolg van 'n verhoging in mikrobe aktiwiteit as gevolg van gunstige grondkondisies.

Bewerking het 'n weglaatbare klein effek gehad op grondwaterinhoud (GWI) die 2014 groeiseisoen. Betekenisvolle verskille is gesien tussen NT en DT na groot reënval gebeurtenisse en aan die einde van die groeiseisoen (P = 0.05). GWI lesings in 2014 het gevarieër tussen 35-270 mm vir alle bewerkingsbehandelings en gewasrotasiestelsels. Bewerking het geen betekenisvolle effek op ET gehad anngesien geen betekenisvolle verskil in ΣET opgemerk is aan die einde van die 2014 groeiseisoen (P = 0.05). Geen betekenisvolle verskil tussen bewerkingsbehandelings is opgemerk gedurende die 2014/2015 braakseisoen. Die totale hoeveelheid reënval opgeneem gedurende die 2015 groeiseisoen was 31% laer as die hoeveelheid opgeneem gedurende 2015. Die hoogste GWI is opgemerk vir die MP behandelings vir alle gewasrotasiesisteme en op verskeie datums is betekenisvol hoër GWI lesings opgeneem vir MP (P = 0.05). MP het geresulteer in 'n betekenisvol hoër ΣET aan die einde van die 2015 groeiseisoen (P = 0.05). As gevolg van 'n tekort aan navorsing oor die onderwerp is geen verklaarbare rede gevind vir die hoë waterinhoud en ΣET onder MP.

In die 2014 groeiseisoen is geen betekenisvolle verskil gevind tussen bewerkingsbehandelings en gewasrotasiestelsels ondersoek terwyl daar in die 2015 groeiseisoen 'n betekenisvolle hoër opbrengs opgeneem is vir NT in die CKLK stelsel (P = 0.9010). Alhoewel die laagste biomassa vir MP opgeneem is is geen betekenisvolle verskil gevind in biomassa resultate nie (P = 0.0274). Wanneer die 2014 en 2015 resultate vergelyk word is 'n 71% verlaging in opbrengs resultate vir kanola opgemerk terwyl 'n 57% verlaging in koring graanopbrengs opgemerk is in 2015. Eenmalige bewerking het geen betekenisvolle effek gehad op waterverbruiksdoeltreffendheid en reënvalverbruiksdoeltreffendheid in beide 2014 en 2015 vir alle bewerkingsbehandelings en gewasrotasiestelsels ondersoek.

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Marianne Williamson

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AWC	Available water content
C	Carbon
CA	Conservation agriculture
CT	Conventional tillage
CWLW	canola/wheat/lupin/wheat
DT	Deep-tine tillage
EC	Electrical conductivity
ET	Evapotranspiration
FDP	Fast drainage pores
HWEC	Hot water extractable carbon
ICP	Inductively coupled plasma
LWCW	lupin/wheat/lupin/wheat
McWMcW	medic/wheat/medic/wheat
MP	Mouldboard plough
MT	Minimum tillage
n-WSA	Non-water stable aggregates
NT	No tillage
OM	Organic matter
PAW	Plant available water
RUE	Rainfall use efficiency
SHC	Saturated hydraulic conductivity
SOC	Soil organic carbon
SOM	Soil organic matter
SWC	Soil water content

SWB	Soil water balance
TOC	Total organic carbon
UHC	Unsaturated hydraulic conductivity
WLWC	wheat/lupin/wheat/canola
WMcWMc	wheat/medic/wheat/medic
WSC	Water stable carbon
WSA	Water stable aggregates
WUE	Water use efficiency
ZT	Zero tillage
ΣET	Cumulative evapotranspiration

Chapter 1: General introduction and research aim

Long-term field experiments investigating different crop rotation systems under conservation tillage were conducted by Elsenburg, Western Cape Department of Agriculture, at Langgewens Research Farm near Moorreesburg, situated in the Western Cape, South Africa. In 2014 the trial was in its 7th year. Conversion to conservation agricultural (CA) practices (e.g. no-tillage and crop rotation) are now increasingly being adopted, as it can improve soil quality, increase agronomic productivity and thereby advance global food security (Lal, 2011). Results obtained from long-term systems trial managed by the Plant Science Directorate proves the benefits of reduced tillage practices, inclusion of diverse crops in a rotation system and maintaining as much stubble as long possible. As the effect of reduced tillage and maximum stubble retention becomes more prevalent, secondary effects, positive or negative, may develop at soil surface level or in the upper layers of the soil profile.

Cavalieri et al. (2009) found that after 14 years of no-till in a sandy clay soil, bulk density was higher, total porosity and macroporosity lower in the 20-30 cm depth compared to 0-20 cm and 30-40 cm. This could serve as proof that a plough pan developed under conventional tillage and negatively influenced certain soil physical properties even 14 years after no-till was introduced. Poirier et al. (2009) also found that the effect of increases in soil organic carbon stocks on converting from conventional tillage to no-till was restricted to the uppermost part of the soil profile. Varvel et al. (2011), however reported opposite results in a temperate region. During a recent farm visit, a medic crop showed severe signs of restricted root penetration due to compaction layers although the experimental plot was under no-till for several years. The question might be asked whether deep tine tillage in this specific case could, in the short term, stimulate more profuse root penetration to the 100-200 mm and thereby enhance organic matter and C built up in the area currently blocked by the partially compacted layer.

No scientifically tested data are available to assist the producer to make an informed decision on tillage management required in abovementioned and similar cases. It is anticipated that similar questions regarding stubble management and tillage will become more common as more producers switch to CA. There is currently no decision making tool available to evaluate the potential negative or positive effects of the strategic use of tillage within CA systems. This study will create guidelines regarding the short- and long-term effects of tillage on selected soil parameters under CA. Both commercial and emerging farmers will be able to use the outcomes of this study as decision making tool to make informed decisions on soil cultivation under CA.

The first objective of this study was to investigate the influence of a once-off tillage operation conducted once in 10 years through a deep tine or mouldboard plough action, of no-till soil on several soil physical and chemical properties and the resultant crop response. The second objective of the study was to investigate the effect of the once-off tillage practices on the soil water balance and the resultant crop response. The third and last objective of the study was to investigate the effect of the different once-off tillage practices on crop performance by determining the water use efficiency and rainfall use efficiency of different crop rotation systems.

Chapter 2: Literature review – Strategic tillage in conservation agriculture

2.1 Understanding conservation agriculture

In the past there has always been a growing concern about the productivity and wider environmental implications of conventional agricultural practices globally. It is especially the intensive tilling of soils by disk, plough or hoe that was of concern. This concern has forced farmers, as well as governments, to explore alternative tillage systems that maintain soil productivity (Knowler and Bradshaw, 2007). The main goal of conservation agriculture (CA) is to make sustainable use of agricultural resources through the integrated management of water, soil and biological resources such that inputs can be lowered (FAO, 2001; Garci' a-Torres et al., 2003). The shift to CA resulted in changes in many soil physical, chemical and biological properties as well as changes in the composition of the soil (Caveness and Kurtz, 1993; Westra and Olson, 1997).

CA is based on the principles of maintaining a permanent soil cover by crop residues or growing crops, avoiding mechanical soil disturbance, and implementing crop rotation. CA includes tillage practices where more than 30% of the soil surface is covered with plant residues (Unger, 1990). The conversion to CA has resulted in both benefits to the farmer, as well as off farm benefits. Benefits to the farmer include increased crop yields, improved soil quality, reduced production costs and more time savings (Phillips and Phillips, 1984) where off farm benefits include less fuel consumption, reduced nutrients entering surface water layers, and increased carbon (C) sequestration during the initial period after conversion from conventional tillage (CT) to CA (Six et al., 2000).

The maintenance of a permanent soil cover by crop residues resulted in water savings of up to 50 %, (Sayre and Hobbs, 2004). The soil cover protects the soil from sun, rain and wind, and thereby it feeds the soil biota. This biotic community provides a so called 'biotic tillage' which replaces the functions of conventional tillage (FAO, 2001). Conservation agriculture (CA) also increases the biotic diversity in the soil as a result of reduced soil disturbance and the surface mulch (Riley et al., 2005). The greater biotic diversity may result in more beneficial insects below and above ground and therefore help to control insect pests. A surface mulch also helps to create favorable conditions for microbial activity, for example, moderate soil temperatures and moisture (Jaipal et al., 2002). Unger (1990), reported an 18% increase in rain storage after the soil surface was covered with 10.1 ton wheat residue.

For the past decade CA has been recognized as the more sustainable cultivation system and the benefits thereof is indefinite. Permanent ground cover showed better infiltration of water (Fabrizzi et al., 2005), reduced water run-off (Freebairn and Boughton, 1985), and more water in the soil throughout the growing season (Kemper and Derpsch, 1981). Mulch resulting from leftover residues helps promote more stable soil aggregates because of increased microbial activity and the better protection of the soil surface (Karlen et al., 1994).

Tillage disrupts the pores left by roots and microbial activity. The bare surface exposed after tillage is prone to the breakdown of soil aggregates as the energy from raindrops is dissipated which results in the clogging of soil pores, compaction, soil erosion, increased run-off and reduced infiltration. Surface crusting may also take place and form a barrier to plant emergence. Soil OM is oxidized when it is exposed to the air by tillage which results in a reduction of the OM content in the soil (Hobbs, 2006).

Research have shown that crop rotations have a disrupting effect on disease and arthropod cycles (Francis and Clegg, 1990). Crop rotations result in higher levels of microbial biomass (McGill et al., 1986) and soil enzyme activities (Khan, 1970; Dick 1984) than cropping sequences that are either continuously monocultured or have more limited crop rotations. Furthermore, diverse crop rotations can change soil habitat by affecting nutrient status, depth of rooting, amount and quality of residue and aggregation (Balota et al., 2002).

2.2 Drivers for strategic tillage in continuous no-till (NT)

Despite of all the benefits of CA there is still a concern about the fact that NT systems could lead to excess soil compaction. Ehlers et al. (1983), found that surface soil layers may become more compacted under NT compared to CT. Several researchers concluded that CA leads to the stratification of nutrients in the surface soil layers (Franzluebbers, 2002; Blanco-Canqui and Lal, 2008; Vu et al., 2009; Deubel et al., 2011). Drivers for strategic tillage also include the build-up of soil- and stubble-borne diseases (Page et al., 2013b; Thomas et al., 1997), the build-up of herbicide resistant weeds (Felton et al., 1994) and the build-up of insect-pests (Wilson et al., 2013). Therefore, the new question arising is what the effect of once-off tillage of a NT crop land will be. Once-off tillage of NT systems refers to a one-time tillage operation which is conducted once in 10 or more years (Quincke, 2006). One-time tillage of NT systems invert the surface layer which contains a high soil organic carbon content with less improved deeper soil (Quincke, 2006).

Stockfish et al., (1999) found that the application of a single mouldboard tillage event to a silt loam soil after 20 years of minimum tillage resulted in dramatic changes in organic matter concentrations. Stockfish concluded that soil organic carbon (SOC) significantly declined with 5.3 mg/ha (11% reduction from original level) in the 0 – 300 mm depth. Two years later the concentration of organic C and organic matter stayed at the same level. Therefore, Stockfish et al., (1999), came to the conclusion that a single tillage operation on minimum tillage plots caused the complete disintegration of all the organic matter and organic carbon that had been accumulated for 20 years.

Pierce et al. (1994) proposed that ploughing periodically should redistribute the stratified nutrients and C caused by NT. He however found in the following year of a one-time mouldboard ploughing event that SOC decreased in the 0- to 50 mm layer while it increased in the 50- to 150 mm depth. In a semiarid climate study conducted in western Nebraska on a silt loam soil Kettler et al. (2000) found that five years after tillage of a no-till soil the SOC content declined 20% in the 0-75 mm layer compared with NT, but increased 15% in the 75-150 mm depth. No change in SOC was found by VandenBygaart and Kay (2004), except for one sandy loam plot with low SOC. This change was found 18 months after a one time ploughing event of a field that was under NT for 22 years in southern Ontario, Canada.

Tillage is highly recommended as one of the control measures for pests that have a soil-inhabiting stage (Downes et al., 2012). The increase of certain pathogens has been attributed to the lack of soil disturbance while for others it is associated with soil surface stubble retention and increased inoculum pressure (Thomas et al., 1997; Page et al., 2013b). Therefore the application of CT and the burial and subsequent decomposition of the stubble leads to the death of numerous stubble-borne pathogens (Bockus and Shroyer, 1998).

2.3 Benefits associated with conservation agriculture (CA)

2.3.1 Soil physical properties

2.3.1.1 Soil texture

Soil texture can be defined as the ratio of sand:silt:clay (Van der Watt and van Rooyen, 1995). Twelve different soil textural classes exist according to their ratios of sand, silt and clay (Van der Watt and Van Rooyen, 1995). Soil texture describes soil physical properties, for example, pore size distribution, the textural class of the soil and bulk density. These in turn determine properties like hydraulic conductivity, soil matrix potential and total porosity (Van der Watt and Van Rooyen, 1995). A clayey soil contains a larger percentage of micro-pores and will result in higher volumetric water contents at a specific matrix potential when compared to sandy soils. Clay retains water more tightly and therefore it will take longer for the soil water content to change over a certain period of time. The soil water content of a sandy soil is generally much higher than that of a clayey soil and therefore the water is more readily available too. Due to a higher hydraulic conductivity in a sandy soil compared to a clayey soil, drainage and evaporation will also occur more easily. Soils with high sand fractions tend to warm faster than clayey soils and therefore the loss of water from the soil due to evaporation is higher. This phenomenon can be explained to higher surface temperatures which results in more available energy for vaporization to take place and thus higher evaporation and water loss from the soil surface.

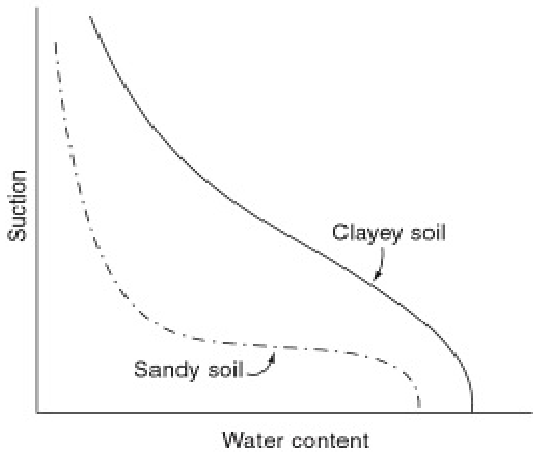


Figure 2.1: Soil water retention curves for different textural classes (Hillel, 1998)

Research conducted by Blevins et al. (1971) showed that no-till result in greater soil moisture content which was attributed to reduced evaporation and a greater ability to store water. This increased storage capability was attributed to a rearrangement of the pore size distribution resulting from the no-till system or the mulch layer. When compared to mouldboard ploughed (MP) soils, NT soils have reduced porosities (Gantzer and Blake, 1978). According to Van Ouwerkerk and Boone (1970) no-tillage not only changes total pore space, but also changes the pore size distribution. They concluded that the finer pores predominate while the larger pores disappear. The same results were obtained by Carter (1992) on a loamy and fine sandy loam soil.

Pagliai et al. (2004) investigated the impact of management practices on the soil structure. The conclusion was that the volume of storage pores (0.5-50 µm) inside the aggregates were greater in the ripper sub-soiling and minimum tillage treatment than was the case in the conventional ploughing treatment. The higher microporosity in ripper and minimum tillage soils could be described by the increased water content in the soil and therefore the increased availability of water to the plants (Pagliai et al., 1995, 1998a). Pagliai (2004) also found that the macroporosity (pores > 50 µm) in the surface layer (0-100 mm) of conventionally tilled soil was lower than in soils under minimum tillage or ripper sub-soiling. The ripped soil showed the highest macroporosity which was evenly distributed throughout the profile. The lowest value of total macroporosity was found in the 400-500 mm conventionally tilled soil layer.

The main aspects to consider for a thorough characterization of soil macropores is pore shape and pore size distribution. It is especially important to make a proper characterization of elongated continuous pores, because many of these pores have a direct influence on plant growth by increasing the storage and transmission of water and gases, as well as easing root penetration (Pagliai et al., 2004). Results obtained by Pagliai et al., (2004), showed that there were less elongated transmission pores in the surface layer (0-100 mm) of conventionally ploughed soils than in the soils under minimum tillage and ripper sub-soiling, as was the case for total macroporosity. In the 400-500 mm layer of soil ploughed to a depth of 400 mm (conventional ploughing), the structure became rather compact due to a strong decrease in elongated transmission pores. A ploughpan at the lower limit of cultivation was well developed.

2.3.1.2 Aggregate stability

A group of particles cohered to each other more strongly than to other surrounding soil particles is known as an aggregate (Kemper and Rosenau, 1986). Whether the cohesive forces between particles can withstand an applied disruptive force is a function of the stability of aggregates (Kemper and Rosenau, 1986). Improved soil structure and aggregation can be achieved by the accumulation of crop residues at the soil surface and a NT system (Six et al., 1998). The formation of aggregates form part of one of the most important processes in C sequestration which allows C to be included and thereby making it inaccessible to decomposing microorganisms (Christensen, 1996). Protection against the disrupting forces of tillage implements will thus be greatest where aggregate stability is high and aggregate turnover is low. Aggregation is the stabilizing mechanism that is potentially most vulnerable to any form of disturbance. The occlusion of organic matter within aggregates serves as a shield against decomposition and therefore stability is provided by restricting the accessibility of microorganisms and their enzymes. Restricted aerobic decomposition due to limited oxygen and extracellular enzymes is also provided (Von Lützow et al. 2006).

Macro-aggregates may be used as possible predictors of potential C responses to tillage. Macro-aggregates plays an important role in protecting recently deposited, labile, light fraction organic matter (Jastrow et al., 1996). Previous studies have shown that newly incorporated crop residues, root derived C, and young soil organic matter (SOM) are found in macro-aggregates (Six et al., 1998; Gale et al., 2000a;

2000b). The disturbance of the soil through tillage causes macro-aggregates to break down (>0.25 mm size) which results in a decreased accumulation of crop-derived C in free micro-aggregates (0.25-0.02 mm size) which forms within macro-aggregates (Six et al., 1998). A slower macro-aggregate turnover leads to more C sequestration in NT due to a higher concentration of C in macro-aggregates compared to micro-aggregates. This phenomenon is explained by the fact that macro-aggregates are composed of micro-aggregtaes and labile organic matter, for example, roots, young plant residues and fungal hyphae (Six et al., 1998; Elliott & Paustian, 2000).

In a previous NT spring wheat system in dryland eastern Montana, USA, it was found that soil aggregation and aggregate stability was improved under NT as compared to CT and increased with time under NT (Martinez and Fuentes, 2008). This pattern was attributed to a greater soil organic carbon content under NT and an increasing amount of basidiomycete fungi as well as a greater proportion of aggregating predominant culturable bacteria in aggregates under NT at 0-5 cm depth (Jabro et al., 2009). At the sub-surface layer (5-20 cm), tillage had no influence on soil aggregation and aggregate stability and tillage had no effect on the amount/proportion of the soil culturable bacteria and soil aggregating basidiomycete fungi. These results were significant to the limited tillage depth (7 cm) in CT which reduced the incorporation of fresh residue into the soil and deep soil disturbance (Jabro, 2009). Research conducted by Six et al. (2000) on a sandy loam and silty clay loam showed that long-term tillage resulted in reduced aggregation. Grandy and Robertson (2006) concluded that tillage of a NT soil immediately destroys macro-aggregates and the reduction persists throughout the growing season.

2.3.1.3 Bulk density

Bulk density is a measure used to determine the state of compactness of a soil (Hakansson et al., 2000). Excessive soil compaction is a major form of soil degradation and can adversely influence soil chemical, biological and physical properties (Carter, 1990). Compaction results in reduced permeability for both air and water and increased physical resistance to root proliferation (Dang et al., 2015). In previous studies it was found that compaction is no greater under NT than CT systems in the deeper soil zones and may be lower in some zones (Gantzer and Blake, 1978). Similar results were found by Lafond (1993); Hammel (1989) and Ferreras et al. (2000). It must be kept in mind that tillage does not consistently affect penetration resistance and bulk density. Factors such as aggregation, soil texture, organic matter content and moisture conditions can influence the sensitivity of the soil to compaction (Marshall and Holmes, 1979). After 8 years under zero-tillage (ZT) system Hill and Cruse (1985), observed increases in penetration resistance as compared to a CT system. However, the bulk density was not affected. In a semi-arid region

Carefoot et al. (1990) observed that bulk density did not differ in clay or loam soils which received 3-8 years of ZT as compared to CT. No differences in bulk density among CT, MT and ZT systems was observed by Chang and Lindwall (1989) after 20 years under a spring cereal-summerfallow rotation on a clay soil. Martino (1991), however examined bulk density and penetration resistance under ZT and CT on a heavy clay soil, a silty clay loam and a loamy sand. He observed a higher penetration resistance in the top 10 cm layer of the heavy clay soil and silt-clay loam under ZT as compared to CT, while the reverse occurred in the lower depths. In the loamy sand no effect was observed, presumably because of its poor structure and the slow rates of macro-pore formation and natural aggregation. According to Wortmann et al. (2010) one-time tillage had no effect on bulk density. During his trials he found that the bulk density was less in the 0-5 cm depth than in the deeper soil.

2.3.1.4 Soil water infiltration

The infiltration rate of a soil may be defined as the volume of water entering a unit area of the soil surface per unit time, while hydraulic conductivity can be defined as the meters water per day that seeps into the soil under the pull of gravity or under a unit hydraulic gradient (Hillel, 1980). Infiltration rates are controlled by several environmental factors, which include, rainfall rates, soil properties (including texture, structure, pore characteristics and organic matter content), vegetation, land use, soil depth, and the initial moisture content (Betson, 1964). As soil becomes increasingly moist infiltration rates decline to a steady or quasi-steady state over the period of rainfall or experimental wetting (Harden and Scruggs, 2003). It is essential to determine accurate infiltration rates for reliable prediction of saturated hydraulic conductivity of the surface layer, amount of surface runoff and groundwater recharge, and in developing or selecting the most efficient irrigation methods. Therefore, the quantification of the soils infiltration capacity is of great importance to understanding and describing the hydrologic analysis and modelling (Lili et al., 2008).

The accumulation of residues and organic matter on the soil surface is one of the most pronounced effects of CA. The mulch layer assists in increased soil biological activity and physical aggregation which improves water infiltration and reduce surface runoff (Shaxson and Barber, 2003). Water runoff in agricultural cropping systems and the resulting soil erosion is a consequence of limited water infiltration (Callebaut et al., 1985; Lal, 1990). Higher infiltration rates, which may be apparent in CA systems, prevent losses of surface water (Callebaut et al., 1985; Lal, 1990). By decreasing surface runoff and improving soil structure and continuous soil pores, higher infiltration will be enabled and therefore available water for crop production will be increased (Shaxson, 2003; Thierfelder et al., 2005).

Voorhees and Lindstrom (1984) found that some soils under no-tillage become more porous with time which enables higher infiltration rates. Other studies found that the ponded infiltration for the NT soils was equal to or greater than that of soils under a CT system (Sauer et al., 1990), even though bulk density was greater and total porosity lower for NT soils. This was attributed to an increased number of continuous earthworm channels that connected the soil surface and a more stable soil structure in the no-till soils. Greater infiltration rates in NT soils compared to CT soils probably resulted from the flow of water through macropores (Meek et al., 1990) and reduced surface sealing due to a complete residue cover (Zuzel et al., 1990). Soil with 100% residue cover facilitated complete infiltration of a 60 mm rainfall, whereas only 20% rain infiltrated when the soil was bare and subject to surface sealing (Roth et al., 1998).

Soil under a NT system had 30-180% greater saturated hydraulic conductivity than the soil tilled with a mouldboard and chisel plow (Benjamin, 1993; Chan and Mead, 1989). Other researchers found that the saturated hydraulic conductivity in tilled and no-till soils did not differ (Obi and Nnabude, 1988) or were lower in NT soils compared to tilled soils (Heard et al., 1988). For example, it was found by Pikul et al., (1990) that water infiltration was greatest on the chisel and paraplow treatment and least on the no-tillage treatment. Inconsistent results of soil hydraulic conductivity under tilled and no-till systems may be related to the transitory nature of soil structure after tillage, site history, initial and final soil water content, time of sampling and the potential for disturbing the soil. Therefore, it is important to remember that the ability of a soil to absorb and transit water is determined by the structural stability of soil pores and the moisture condition of the soil at the time of measurement, both of which can be modified by tillage practices (Azooz et al., 1996).

2.3.1.5 Soil water content and soil water balance

In the Swartland, a semi-arid sub region of the Western Cape, water is one of the most important limiting climatic factors for crop production (Hoffman, 1990). The climate is typical Mediterranean with annual rainfall ranging between 401-600 mm (Palmer and Ainslie, 2006). Although the Western Cape is a winter rainfall area it is also the second driest province in South Africa (Benhin, 2006). According to previous research conducted at Langgewens in 2012 and 2013 most of the rainfall occurred during June and September (Swiegelaar, 2014). The rainfall in the Western Cape is very erratic and does not always ensure continuous high yields, when combined with increased temperatures, for dry-land crop production. Under such climatic conditions the water stored in the soil profile is the most important factor to stabilise and increase yields. The storage efficiency of a soil can be described as the portion of total precipitation that is stored in the soil profile during certain periods of time (Deibert et al., 1982). According to Deibert et al.

(1982) many factors can influence storage efficiency, for example, total precipitation, soil type, and most importantly the type of soil management practiced; specifically the tillage and cropping system. The Swartland is known for its shallow, shaley soils which contains a high percentage of coarse fragments (Tankard et al., 1982). All these factors contribute to a poor water holding capacity which can lead to detrimental plant effects when considering the fact that not much water can be stored during short periods of drought. In dry-land farming systems it is important for the soil to have a high water holding capacity to ensure that there is enough water stored in the soil profile during periods of drought which can buffer the crop during these periods. Therefore, tillage is an option to address a particular situation, for example, to increase water availability for crops by reducing evaporation, increasing infiltration, eliminating weed competition, and allowing a better development of root systems (Lampurlanés et al., 2000).

CA in the Western Cape has become a very popular management option for farmers in the past 2-3 decades due to the ability to increase soil water storage. CA is based on the principles of maintaining a permanent soil cover by crop residues or growing crops, avoiding mechanical soil disturbance, and implementing crop rotation (Unger, 1990; Fabrizzi et al., 2004; De Vita et al., 2006). Thereby, the sustainable use of agricultural resources can be achieved through the integrated management of water, soil and biological resources (FAO, 2001; Garci' a-Torres et al., 2003). The soil water balance could be an important tool to assess the effects of environmental management of cropped fields on soil and crop performance (Hillel, 1998). Calculating the water balance, various soil related parameters such as runoff, drainage/deep percolation and evaporation from the soil surface can be estimated (Hillel, 1998). Abovementioned factors are without exception influenced by the long term effects of different tillage practises (Lampurlanés et al., 2000; Kovac et al., 2005; Quincke et al., 2007b), cropping systems (Deibert et al., 1982; Sayre and Hobbs, 2004) and stubble management (Jaipal et al., 2002; Unger, 1990).

According to Lampurlanés et al. (2000) CA nearly always increased stored soil water by reducing evaporation, increasing infiltration and thereby increasing yield depending on the climate and soil conditions. Similar results were obtained by Lal, (1975); Fisher, (1987); Meek et al. (1990); Unger et al. (1991) and Rinaldi et al. (2000). However, decreases in stored soil water were observed by several authors (Hill, 1990; Thorburn, 1992; Vyn and Raimbault, 1993). Reduced soil disturbance increases microbial activity and results in higher soil organic matter contents which lead to a more stable soil pore system as well as improved aggregate development (Kladviko et al., 1986; Six et al., 2002). An improved soil pore system and soil structure will enable higher water infiltration and will eventually increase yields due to increased available water for crop production (Roth et al., 1988; Shaxson, 2003; Thierfelder et al., 2005).

The maintenance of a permanent soil cover by crop residues resulted in water savings of up to 50 %, (Sayre and Hobbs, 2004). According to Dardanelli et al. (1994) a mulch layer impedes evaporation of water from the soil surface by protecting it from direct solar radiation and air flow across the soil surface leading to higher soil water contents. A surface mulch also helps to create favourable conditions for microbial activity, for example, moderate soil temperatures and moisture which in turn increases the soil organic matter content (Jaipal et al., 2002). Unger (1990), reported an 18% increase in rain storage after the soil surface was covered with 10.1 ton wheat residue. Many researchers reported that CA systems result in reduced runoff, increased SOM (Buschiazzo et al., 1998; Thomas et al., 2007; Unger, 1991) an increased total porosity (TP) (Lipiec et al., 2006; Malumba and Lal, 2008) improved aggregate stability (Blanco-Canqui and Lal, 2007; Keller et al., 2007) which in turn increases the soil moisture content (SMC) (Govaerts et al., 2007; Gruber et al., 2011; Sharma et al., 2011) available water content (AWC) (Bescansa et al., 2006) and infiltration (Bhattacharyya et al., 2006). Water runoff and the resulting soil erosion in agricultural systems is a consequence of limited water infiltration, compacted subsoils and hardpans/reduced macropores (Callebaut, 1985; Lal, 1990). Results obtained by Thierfelder (2003) have shown that between 10-22% of rain water are lost from an uncovered, ploughed soil surface. Water infiltration and sorptivity were increased with a once-off MP tillage action of NT soil (Quincke et al., 2007b). Rockström et al. (2001) compared CA to conventional systems and reported that 10-25% of rain water are lost to runoff and another 30-50% through evaporation due to an uncovered soil surface. De Vita et al. (2007) and Bonfil et al. (1999) found that CA result in both increased water use efficiency (WUE) as well as grain yield due to minimized evaporative losses from the soil. Thierfelder et al. (2009) found similar results on rainfall use efficiency (RUE). Higher yields were also attributed to decreased evaporation and increased infiltration.

2.3.2 Soil chemical properties

2.3.2.1 pH, EC and other chemical properties

Concern is developing about the fact that NT systems may lead to nutrient stratification (Karlen et al., 1991). Decreases in surface soil pH is another factor under concern due to the fact that such changes could influence nutrient availability and the leaching thereof (Karlen et al., 1991). NT systems result in the concentration of relative immobile nutrients (e.g. N, P, K, Ca, Mg & Na) in the upper soil layers due to the absence of inversion and mixing of surface soil layers (Karlen et al., 1991; Thomas et al., 2007). According to several researchers, when comparing NT and CT systems, soils are frequently more acidic in the surface layers and less acidic in the deeper layers. This phenomenon can be attributed to an increase in organic matter (OM) and associated organic acids, as well as changes in cation and anion proportions in soils under NT practice (Kern & Johnson, 1993).

2.3.2.2 Soil organic carbon (SOC) and carbon dioxide (CO_2) efflux

SOC affects various soil physical, chemical and biological properties and is one of the primary indicators of agricultural sustainability and soil quality (Lal, 2011). Not only does the carbon pool affect soil quality, but CO_2, which is an end product of SOM, is also one of the greenhouse gases responsible for the known phenomenon global warming. Soils can act as either a sink or source for CO_2 depending on the management system (e.g. conservation- of conventional agriculture). Management systems have a direct influence on SOC mineralization (Lal, 2011). Therefore, it is of utmost importance to identify and quantify the effect of different management systems on soil C stabilization to prevent C losses and therefore soil degradation (Rasmussen & Albrecht, 1997).

Tillage accelerates the oxidation of organic matter through soil microorganisms by changing the water content, aeration and temperature of the soil (Doran and Smith, 1987). Therefore, soils under NT generally tend to contain a greater amount of organic C compared to CT soils, especially closer to the soil surface (Thomas et al, 2007). According to Lal & Bruce (1999), the SOC content is increased by implementing crop rotation and no-till procedures which retains crop residues close to the surface of the soil and attributed it to increased crop residue retention and biomass production. Increased SOC in the 0-5 cm surface soil is common with NT (Blanco-Canqui and Lal, 2008), although the deep SOC balance is lower with NT compared to CT systems with no long-term increase in SOC (Baker et al., 2007). Most of the accumulation of SOC in the surface soil occurs during the first ten years of NT with no or lower increase of SOC in later years (Omonode et al., 2006). The stratification of C in the surface soil layers is a general problem under NT and therefore it is a necessity to mix or invert the surface soil layers in order to redistribute C and other nutrients (Franzluebbers, 2002).

Intensive tillage, particularly moldboard plowing, can cause large gaseous losses of C from the soil when compared to NT. The reason for the large CO_2 loss can be explained by the fact that the moldboard plow fractures, inverts and opens the soil which allows for rapid CO_2 and O_2 exchange. At the same time the mouldboard plow incorporates residues into the soil which feeds an exploding microbial population (Reicosky, 1997; Quincke et al., 2007). CA leaves most of the crop residues at the soil surface leaving only a small portion in direct contact with the soil moisture and available to microorganisms resulting in slower residue decomposition (Reicosky, 1997; Quincke et al., 2007). CA can potentially contribute to the lowering of greenhouse gas emissions within the agricultural sector and various studies have concluded that reduced tillage results in increased SOC (Bhattacharyya et al., 2012). From various studies it was evident that different crop rotation and tillage practices can play a vital role in the stabilization of SOC and thereby increase soil quality and productivity and partially mitigating the current increase in atmospheric CO_2. However, this contribution is dependent on both soil and climate conditions.

2.3.2.3 Soil organic matter (SOM)

The accumulation of residues and organic matter on the soil surface is one of the most pronounced effects of CA. A Brazilian study by Sisti et al. (2004) also concluded that an increased accumulation of OM by using a legume in the rotation system can be achieved. Several studies have shown that not only is there a redistribution or stratification within the soil, but CA maintains higher total amounts of organic matter in the soil than do CT (Rasmussen et al., 1988). Increased surface concentrations of soil organic matter relates to improved soil physical properties and water management (Sprague and Triplett, 1986).

According to Machraoui (2010), SOC and thereby SOM contents are higher with NT than with CT in the 0-20 cm profile depth. Although, results were not significant due to short time use of NT or soil structure because clay- and silt-associated SOM is more stable and does not readily change with management (Six et al., 2001). The amount of clay in the soil determines the amount of SOM loss due to tillage. In fine textured soils the SOM loss is lower (Hassink, 1995). It was found that the fine textured soils as well as clay- and silt-sized particles with high surface activity chemically stabilize SOM and therefore form the building blocks for aggregates and thereby induce physical protection of SOM by occlusion in aggregates (Six et al., 2000). Six et al. (2002), also found that the soil structure of four sites (clay-silt) provides potential for the stabilization of SOC by the association of organic materials with clay minerals and the formation and stabilization of the organic materials within aggregates (Six et al., 2002). CT will reduce the stabilization of SOC within aggregates by enhancing soil structural degradation and aggregate breakdown (Chivenge et al., 2007).

A long-term field experiment conducted by Stockfish et al. (1999) concluded that silt loam soils will concentrate SOM near the soil surface when inversion tillage is abandoned and conservation tillage is adopted. They also concluded that the specific accumulated SOM is of labile character because it decomposes rapidly and completely after re-starting mouldboard ploughing. The enriched fraction near the soil surface is also more easily decomposable than other fractions of organic matter due to its position in the soil. Therefore, the fraction is prevented from rapid disintegration due to less accessibility and due to temperature and moisture fluctuations. After ploughing, the prevention of rapid disintegration is neutralized and the microbial decomposition of the stored SOM is rapid when weather conditions are favorable.

2.3.2.4 Active carbon (Hot water extractable carbon (HWEC))

Active carbon, also known as labile fractions of soil organic matter, is a C pool that is easily decomposed by soil microbes and is easily lost and mostly affected through tillage in the short term when comparing humified fractions (Weil et al., 2003). Two labile organic C pools exist in the soil and differ with decomposition rates and turnover times (Parton et al., 1987). The active C pool is mainly compiled out of microbial biomass, soluble carbohydrates, and exocellular enzymes. Although active C forms part of a very small proportion of soil organic matter, it is involved in many processes in the soil (McGill et al., 1986). These molecules have an influence on soil biological activity (Xu and Juma, 1993), has an effect on the transport of metals and organic pollutants (Römkens and Dolfing, 1998), and makes an contribution to mineral weathering (Rauland-Rasmussen et al., 1998) and Podzolization (Van Hees and Lindström, 2000).

The type of plant species determines the amount and type of C input to the soil (Campbell et al., 1999). Therefore, it is evident that crop rotations in agricultural soils may influence the active C concentration from year to year. The inclusion of legumes into the rotation system increases the amount of active C present in the soil by 2-44 kg ha^{-1} (Mazzarino et al., 1993; Campbell et al., 1996). Chantigny et al., (1997) concluded that the active C content was generally higher under legumes than under gramineae species for two consecutive growing seasons in a clay loam soil.

It was found that soil tillage has a definite effect on active C (Gregorich et al., 2000). Balota et al., (2002) came to the conclusion that active C varied from 163 to 209 µg g^{-1} in soils under CT and from 204 to 367 µg g^{-1} in soils under NT. The increase in active C under NT compared to CT was attributed to several factors. An important factor was the lowering of soil temperature due to the presence of surface litter in a NT system. The accumulation of crop residues at the soil surface provides substrates for soil micro-organisms, therefore NT leads to a higher active C content at the soil surface.

Research conducted by Quincke (2006) after the application of a mouldboard ploughing event concluded that the labile organic matter pools were reduced by an estimate total of 24-88% in the 0-25 mm depth and increased by an estimate total of 13-81% in the 50-100 mm depth. Leinweber et al., 2001, came to the conclusion that an increase in tillage intensity altered the soil active C composition. It was suggested that an increased tillage intensity enhanced oxidative microbial activity.

2.4 Problems associated with CA

2.4.1 Soil physical properties

2.4.1.1 Bulk density

One of the main aims of tillage is to reduce bulk density and hence soil strength within the A horizon of soils to promote root growth within the tilled top layer and the subsoil (Barber, 1971). Bulk density (Ehlers, 1973) and soil strength (Ellis et al., 1979) within the A horizon increases when regular cultivation is abandoned and ZT is incorporated, but not to an extent where root growth is influenced. However, in the deeper soil zones NT had no effect on either bulk density or penetration resistance whereas CT caused detrimental densities and resistances that restricted soil aeration and crop root development, restricted water uptake, nutrient availability and overall crop growth (Lafond, 1993 and Henderson, 1991).

Jemai et al. (2013) found that the practice of CA without addition of mulch residues increases bulk density within the near soil surface. An increase in bulk density and decrease in total porosity until a depth of 30 cm under NT was also observed by Jemai et al. (2013). The destruction of total porosity and bulk density in the rooting zone under NT was ascribed to soil compaction induced by traffic using heavy, wheeled farm machines Hamza and Anderson, 2005). The study indicated that an increase in bulk density only appeared to be temporary and was later compensated by the development of soil pores which originated from biological activity, including roots and earthworms.

Research conducted by Botha (2012) at Langgewens Research Farm near Moorreesburg concluded that tillage only has a decreasing effect on bulk density for a time period of 30 days (*Figure 2.2*), thereafter bulk density values increase and return to values obtained before tillage took place.

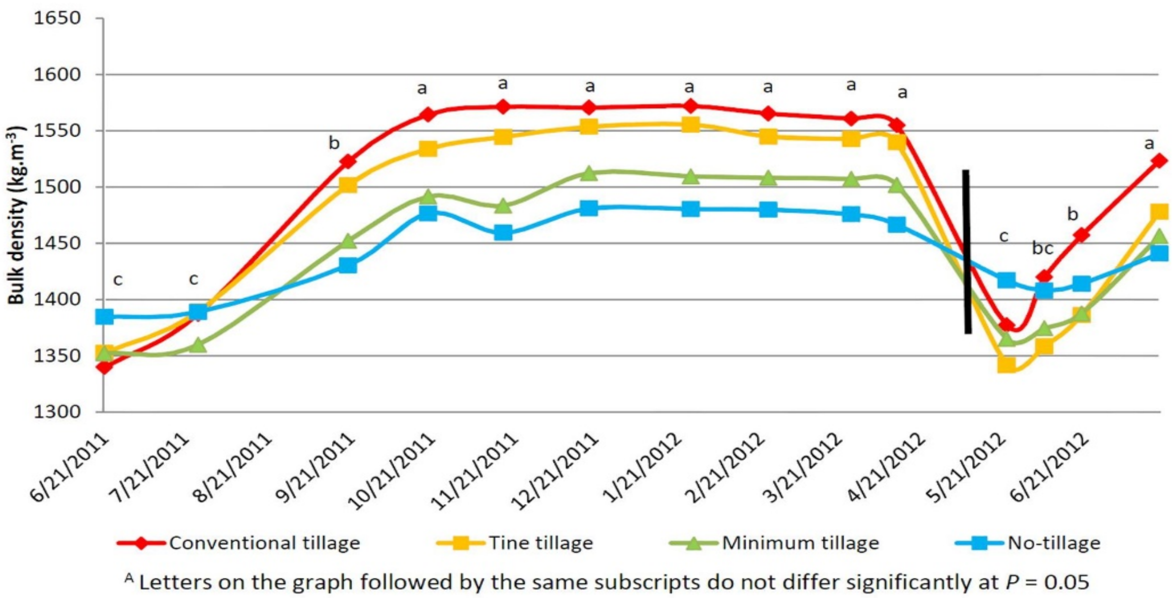


Figure 2.2: The effect of different tillage treatments on the soil bulk density (De Clercq and Botha, 2012)

Fabrizzi et al., (2005) concluded that NT leads to significantly higher bulk densities and lower total porosities, which indicated that a lack of disturbance produces an increase in soil compaction. However, bulk density values were below the range of 1.4-1.5 $Mg.m^{-3}$ as affecting root growth. Other researchers found that bulk density increased from 1.23-1.31 $Mg.m^{-3}$ at 3-8 cm and from 1.26-1.34 $Mg.m^{-3}$ at 13-18 cm soil depth in a period of two years under NT. After another two-year period bulk density values were slightly lower (1.26 $Mg.m^{-3}$) on the surface and similar values were found on the 13-18 cm soil depth. These results indicated that bulk density tends to stabilize after 5 years in a NT system.

2.4.1.2 Soil water infiltration

Infiltration rates are greatly affected by tillage treatments. Conventional tillage creates macropores in the soil that facilitate infiltration, especially after plowing (Reyes et al., 2002). Reyes (2002) found that there is a greater amount of fast drainage pores (FDP) under CT than under NT. At harvesting, the repacking of soil aggregates might lessen the amount of FDP created by tillage. It is possible that the increased amount of OC under NT may counteract the slow infiltration rate of the soil. Under NT the soil water infiltration and coarse porosity decreases and this may lead to a delay in root growth, the cause of root diseases, runoff and erosion under rainy conditions or in over irrigated systems.

Soil infiltration is directly related to structural stability (Tisdall and Adem, 1986), pore structure (Ankeny et al., 1990) and bulk density (Patel and Singh, 1981). Bennie and Burger (1979) found that the hydraulic conductivity, as well as the final infiltration ability of saturated apedal topsoils decreases with a clay and silt increase. Long-term CT and NT systems can alter aggregate stability, bulk density, total porosity and total organic carbon content (Lal et al., 1994; Singh et al. 1994), thereby altering soil structure as well as the various factors affecting the water storage capacity and water transmission properties of the soil. CT systems compact the soil below the tilled zone, increase the breakdown of residues (Carter and Colwick, 1971) disrupt surface-vented pores and increase surface sealing (Roth et al., 1998). Therefore, tilled soils under continuous cultivation tend to become less porous in the plow layer with time.

The lower infiltration rate with CT compared to NT can result from aggregate destruction and the formation of surface seals in the CT soil (Arshad and Mermut, 1988) which was exposed to direct rain drop impact. A lower aggregate stability, increased compaction and reduced average pore size distribution in the surface soil can be contributed to a lower organic matter content in tilled soils (McIntyre, 1958 and Agassi et al., 1985). Pores were preserved in NT soils and a higher percent of residue cover protected the soil surface from raindrop impact. Even though soils under NT retained more water than soils under CT, infiltration rates in CT soils decreased more significantly with time (more negative slope) than was the case with infiltration rates in NT soils (Azooz et al., 1996).

2.4.2 Soil chemical properties

2.4.2.1 Soil organic carbon (SOC)

Several researchers concluded that CA leads to the stratification of nutrients in the surface soil layers (Franzluebbers, 2002; Blanco-Canqui and Lal, 2008; Vu et al., 2009; Deubel et al., 2011; Bell et al., 2012). NT results in a lower SOC content in the deeper soil zones (Blanco-Canqui and Lal, 2008) which can be a result of poor root growth under NT compared to CT. Significant loss of SOC with one-time MP tillage of NT land has been reported (Stockfisch et al., 1999) but when SOC was measured on an equivalent mass basis no loss was detected in other studies (Van den Bygaart and Kay, 1994).

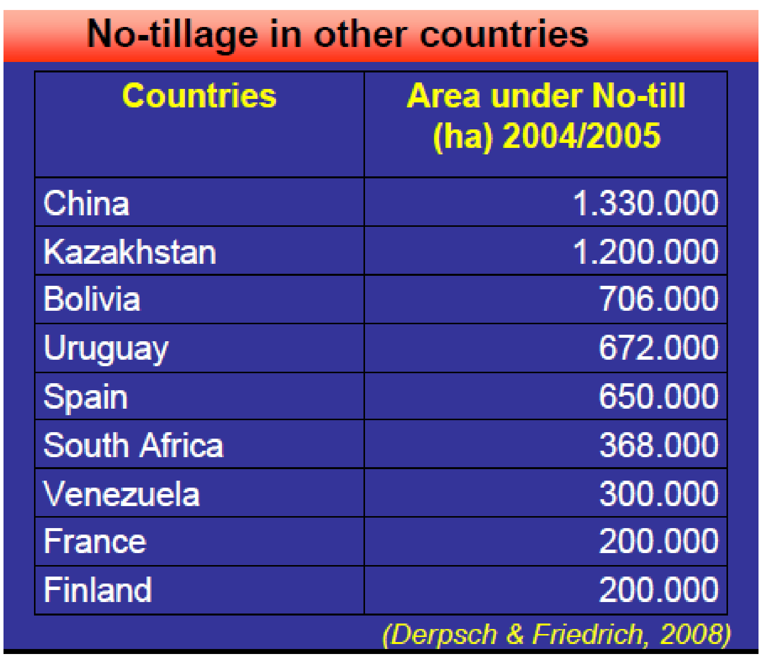
2.4.2.2 Soil organic matter (SOM)

Several studies have shown that CA maintains higher amounts of SOM in the soil profile than do CT (Dick, 1983; Gallaher and Ferrer, 1987; Rasmussen and Rohde, 1988). The increased amounts of residue and soil organic matter in the surface soil can have negative effects on crop production. Increased organic matter concentrations can severely reduce the effectiveness of certain pre-emergence herbicides. The reduction is closely tied with the fulvic acid carbon fraction (Stearmanet al., 1989). Surface residues may also lead to increased plant disease pressures by providing a habitat for growth, overwintering (survival) and multiplication of plant pathogens (Boosalis et al., 1986), mineral nutrients and pH. Conservation tillage practices applied in temperate zone regions can rapidly increase surface soil acidity (Blevins et al., 1984).

2.5 The evolution of CA

2.5.1 An international view of CA

In the past minimum tillage (MT) practices have often been labelled as NT by farmers. This is however not the case, because MT practices in general are not able to sequester C in the soil, while NT does sequester C and is able to result in an increase in organic matter content in the soil if the three principles of CA is followed (Derpsch and Friedrich, 2008). As already mentioned, the three principles of CA is the maintenance of a permanent soil cover, minimum soil disturbance while implementing a diversified crop rotation system (Derpsch, 2008). Research conducted by Derpsch and Friedrich (2008) have shown that NT cover cropping systems have worked in all kinds of environments. From Kenya and Uganda (the Equator) to Argentina and Finland, as well as from sea level to 3000 m above sea level. It is also a successful practice on 90% sand soils (Australia and Brazil) as well as 85% clay soils (Brazil) and the positive results is evident in 250 mm (Western Australia) of rain to 2000 mm (Brazil) or 3000 mm (Chile) of rain. CA have been adopted worldwide. All of the following countries have successfully implemented the CA system: USA, Brazil, Argentina, Canada, Australia, Kazakhstan, Paraguay, Chile, Switzerland, Kenya, Africa and North Korea. All crops can be seeded in CA systems, for example; potato after rice in North Korea (Friedrich, 2006), potato after wheat in Colombia (Birbaumer, 2000), and sugar cane into Crotalaria juncea in Brazil (Calegan, 2008).



No-tillage in other countries

Countries	Area under No-till (ha) 2004/2005
China	1.330.000
Kazakhstan	1.200.000
Bolivia	706.000
Uruguay	672.000
Spain	650.000
South Africa	368.000
Venezuela	300.000
France	200.000
Finland	200.000

(Derpsch & Friedrich, 2008)

Figure 2.3: Area under NT (ha) in other countries in 2004/2005 (Derpsch and Friedrich, 2008)

World total 105 Million ha

Continent	Area (hectares)	Percent of total
South America	49.579.000	46.8%
North America	40.074.000	37.8
Australia & New Zealand	12.162.000	11.5
Asia	2.530.000	2.3
Europe	1.150.000	1.1
Africa	368.000	0.3
World total	**105.863.000**	**100%**

(Derpsch & Friedrich, 2008)

Figure 2.4: Area under NT and % by continent (Derpsch and Friedrich, 2008)

In the last 20 years there has been a remarkable 150% increase in the total production of grain in Argentina from 1987/1988 to 2007/2008. At the same time, the cultivated surface area only increased with 53%. It was found that the major increase was due to an increase in productivity which was a result of higher C sequestration and a higher SOM content (AAPRESID, 2008). Therefore, CA systems have reversed the former trend of decline in crop productivity and resulted in an ecologically and socially sustainable, as well as an economically sustainable form of commercial cropping in South America (CIMMYT, 2002).

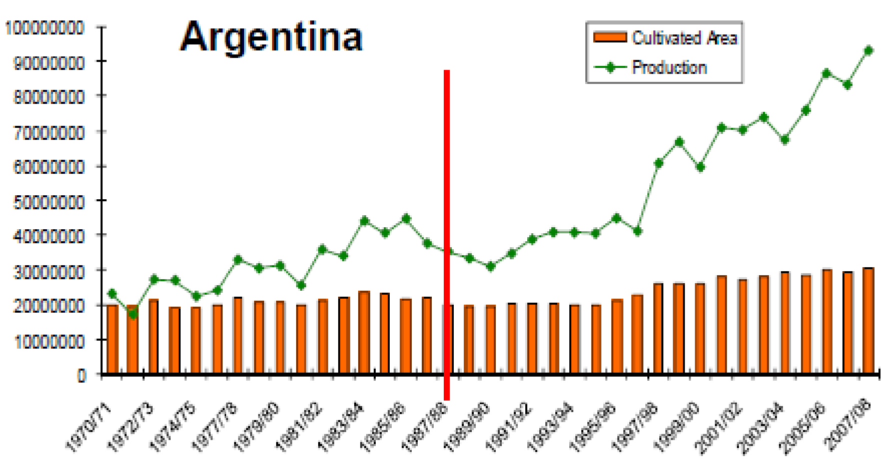


Figure 2.5: Increase in grain production from 87/88 to 07/08 vs growth in cultivated area (AAPRESID, 2008)

2.5.2 A national view of CA (South Africa)

Research was conducted by Hoffman et al., (1994) in Bloemfontein, Tweespruit, Hoopstad and Petrusburg in the Freestate, South Africa. They concluded that run-off was higher in untilled soil and that the infiltration of water will increase, in this case, if tillage was conducted. They attributed the increase in run-off to wetter soils which was indirectly related to a higher clay and silt content. The implementation of a surface mulch (10-50% soil coverage) had no positive effect on the ability of the soil to store rainfall and therefore the surface mulch was unsuccessful in reducing evaporation and run-off. Several crop related results were obtained by Hoffman et al., (1994). The highest wheat yields were obtained under CT. No-tillage practices resulted in the lowest yields for wheat, especially where soils were sandy. In the case of the implementation of crop rotation systems, higher yields were obtained compared to NT. The increase in wheat yield was attributed to a presence of a water table during planting time. Wheat is grown during the low rainfall winter-spring season and therefore the stored plant available water (PAW) makes an important contribution to the supply of water to the plant. Root development was lower in the case of NT compared to CT. Especially clayey soils resulted in lower root development and distribution under NT. The main hypothesis of the researchers was that the production of wheat increases during seasons with low rainfall if the PAW increases during planting time. The higher the rainfall during the growing season, the less PAW is stored and used, and the lower is the capacity to store water during the next rainfall period. Therefore, higher WUE were obtained for wheat crops under CT practices. The researchers concluded that a higher WUE can result in deep sandy soils with a clay and silt percentage lower than 15% (Hoffman et al., 1994).

2.6 Conclusion

Conservation agriculture has become a very popular management practice in the Western Cape. The positive effects of CA are well known, although, some negative effects may develop over time. Nutrient stratification, increased bulk density and increased crop residue cover may result in problematic effects in the soil. These effects may be addressed through, amongst others, the cultivation of soil. The cultivation of soil may affect the physical and chemical quality of the soil as well as soil water relations. Until now, limited information was available regarding the effect of strategic tillage of no-till soil on selected soil physical, chemical and water related properties. Previous research has shown that both positive and negative soil properties may result after the application of a once-off tillage action. However, there is a gap in knowledge on how a once-off tillage practice will affect soil properties in the grain production regions of South Africa. The Western Cape is the most important wheat producing region in South

Africa. The majority of wheat farmers in the Western Cape apply dry land farming and therefore they are very dependent of rainwater. It is therefore crucial for the farmer to understand the principles behind his management strategies in order to ensure the efficient and sustainable use of the available resources.

Chapter 3: Materials and methods

3.1 Locality

The study was conducted during 2014 to 2015 at the Langgewens Research Farm managed by the Western Cape Department of Agriculture near Moorreesburg ($33^0$16'42.33" S; $18^0$42'11.62" E; 191m), South Africa. The trial formed part of a long term trail started in 2007. The dominant soil forms were Glenrosa (GS) and Swartland (SW) (*Figure 3.1*) which constituted 65 % and 35 % of the total experimental area, respectively. The lithocutanic B horizon of both the Glenrosa and Swartland soil forms contained a very large percentage of soft philite (shale) fragments and therefore these horizons contained a high percentage of coarse fragments which may have a significant effect on the water holding capacity of these shallow soils. The clay content of the upper 0-30 cm was between 10-15%. The soils were classified as sandy loam soils.

3.2 Soil

Soils were classified during a research trial conducted from 2012 through to 2013 (*Figure 3.2*). A total of nine soil profile pits were classified according to the binomial soil classification system for South African soils (Soil Classification Working Group, 1991. Due to the position of the soil form in the landscape, soil forms differed in their degree of weathering of underlying material. The underlying material had an influence on the crop production suitability rate due to the fact that the soils are hard and shallow in the dry state. The effective depth of the soils varied between 600 mm and 90 cm. The A horizon had inconsistent depths which varied between 0-300 mm and 0-400 mm. The A horizons found at the crest were even more shallow. The B horizons varied between 300-900 mm and 400-1000 mm in depth. The lithocutanic B horizon of the Glenrosa soil form contained a very large percentage of soft phillite (shale) fragments. The A horizon contained a high percentage of coarse fragments which may have a big effect on the water holding capacity of these shallow soils. The clay content of the upper 0-30 cm was between 10-15%. The soils were classified as sandy loam soils. A thorough description of each of the nine soil profile pits classified can be found in Appendix A.

(a) **(b)**

Figure 3.1: Digital images of the soil profiles which dominated the experimental site at Langgewens Research Farm (a) Glenrosa soil form under wheat (b) Swartland soil form under canola.

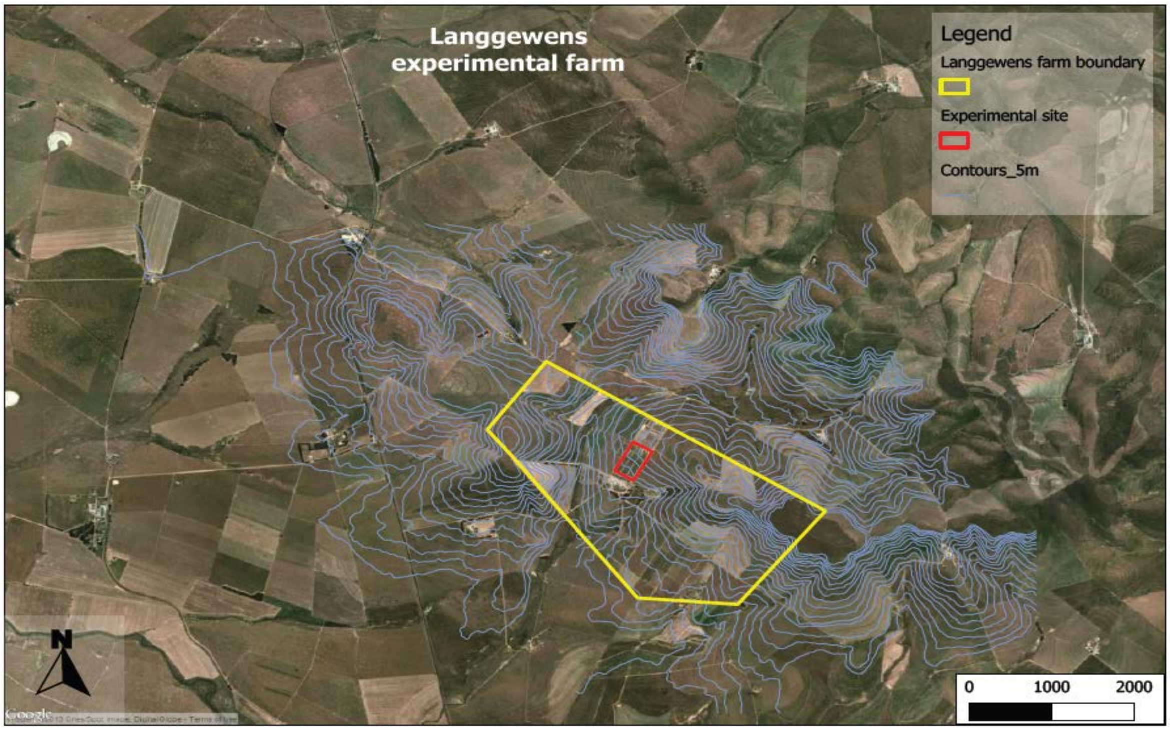


Figure 3.2: Location of the study site at the Langgewens Research Farm, Moorreesburg (Swiegelaar, 2013).

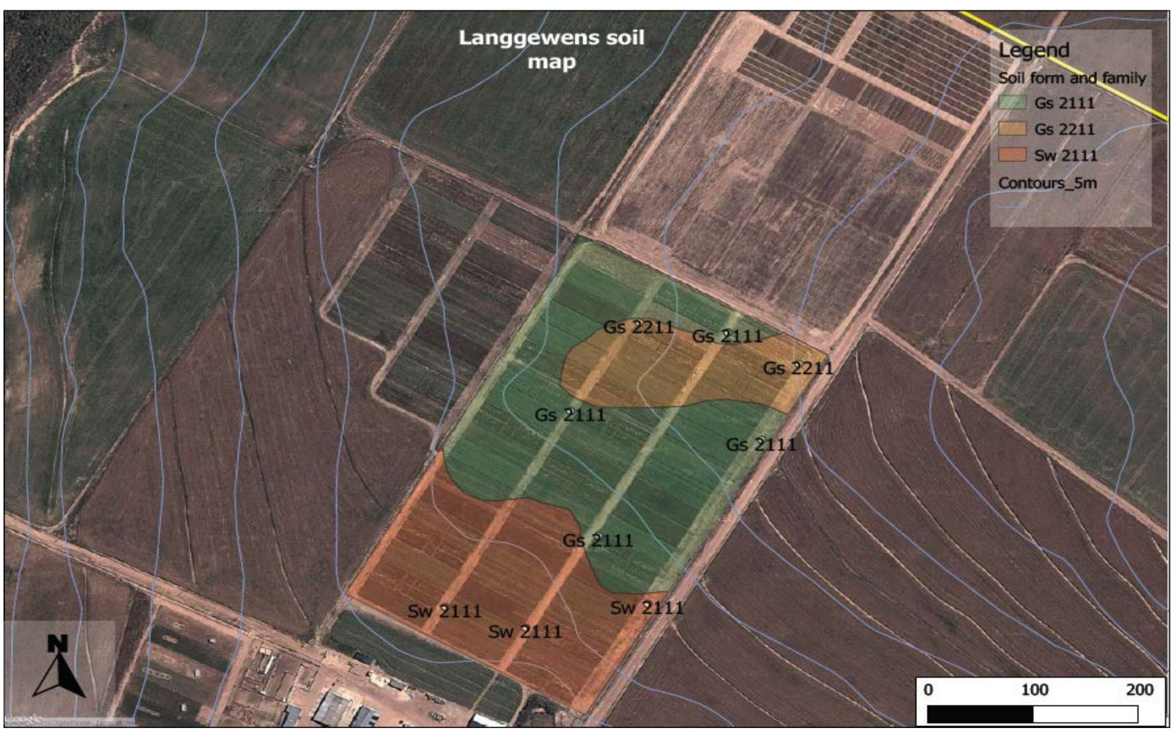


Figure 3.3: Location of the soil forms included in the study site at the Langgewens Research Farm, Moorreesburg (Swiegelaar, 2013)

Table 3.1: The soil forms which dominated in various treatments

Treatment	Tillage system	Rotation system	Soil form
1	NT	McWMcW	Glenrosa
2	NT	LWCW	Glenrosa
3	NT	WLWC	Glenrosa/Swartland
4	MP	McWMcW	Glenrosa
5	MP	LWCW	Glenrosa
6	MP	WLWC	Glenrosa/Swartland
7	DT	McWMcW	Glenrosa
8	DT	LWCW	Glenrosa
9	DT	WLWC	Glenrosa/Swartland

3.3 Climate

The Swartland climate is typical Mediterranean and therefore the majority of the annual rainfall is received during the winter. The winter is mostly cold and wet and the summers is characterized with hot and dry climate conditions (Figure 3.4 and 3.5).

In 2014 a total of 270 mm rainfall was recorded during the 2014 growing season (*Figure 3.4*). The majority of the rainfall occurred between May and September with 62 % of the total rainfall recorded in this period. Three major rainfall events took place on the 19th of June, 30th of July and 3rd of September which led to increases in soil water content (SWC). Unusual high temperatures were recorded on the 14th of July and 12th of August which resulted in sharp decreases in SWC. Increases and decreases in SWC had a major impact on the soil water balance and therefore the development and growth of crops.

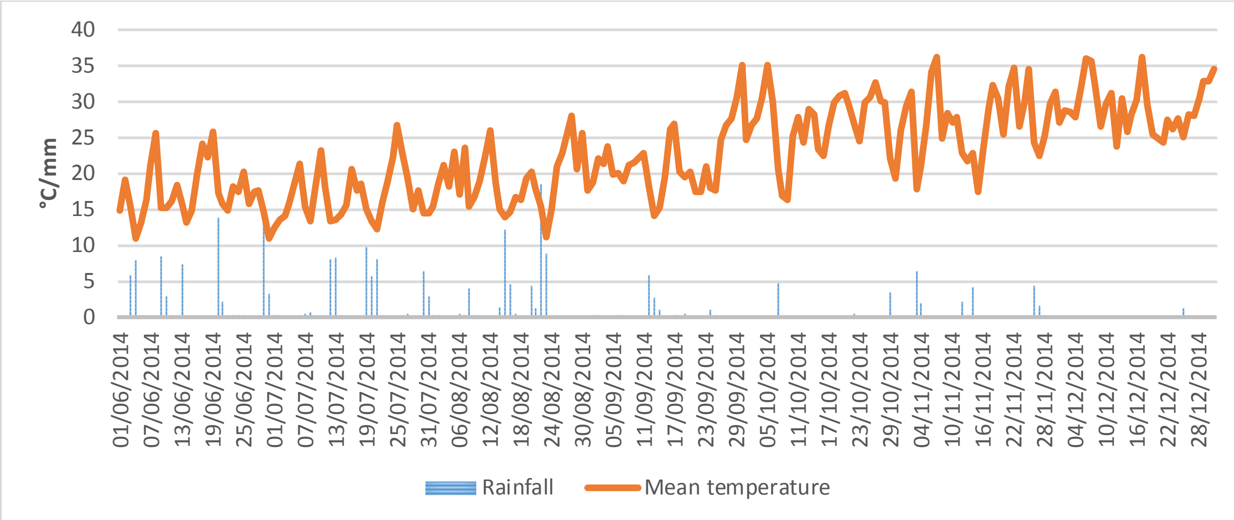


Figure 3.4: Mean daily temperatures (°C) and rainfall incidents (mm) at Langgewens (2014)

In comparison 2015 was a very dry year compared to 2014 with 31% less rainfall recorded during the 2015 growing season (*Figure 3.5*). A total of 169 mm rainfall was recorded during the 2015 growing season. In 2015 the majority of the rainfall occurred between May and July with 67% of the total rainfall recorded in this period. Three major rainfall events took place on 2 June, 16 June and 17 July (between 14-17 mm) which led to increases in soil water content (SWC). Unusual high temperatures were recorded on 3 March, 22 May and 10 October which resulted in sharp decreases in SWC. On 27 October, harvest day, a temperature of 40°C was recorded. An average temperature of 20°C was recorded for the 2015 growing season.

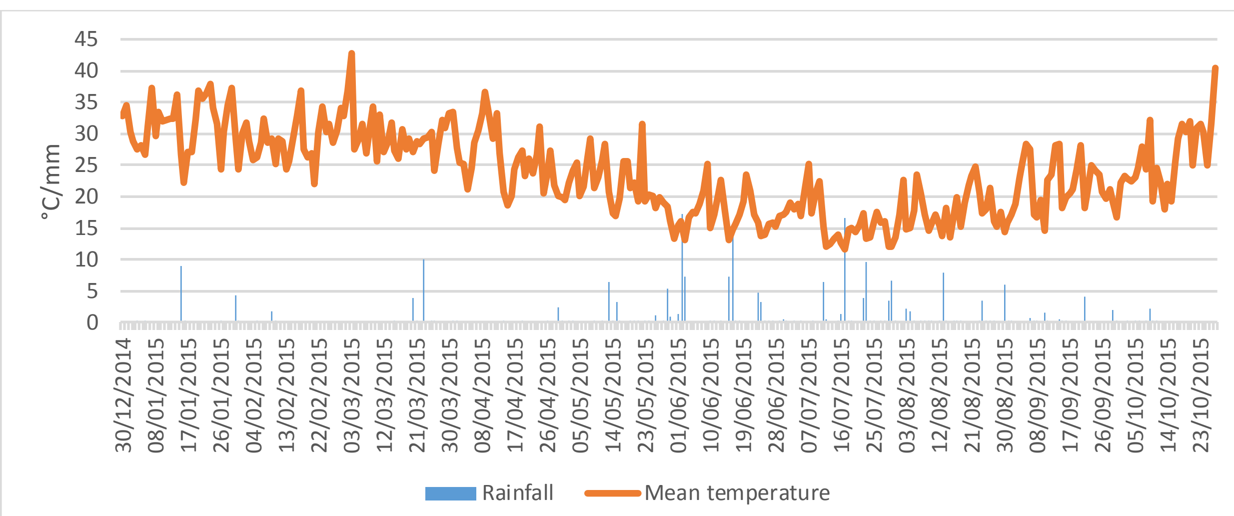


Figure 3.5: Mean daily temperatures (°C) and rainfall incidents (mm) at Langgewens (2015)

3.4 Treatments and experimental design

The study was conducted using a randomised complete block experimental design with a split-plot treatment. The experimental gross plot size was 60 m × 5 m of which 30 m was used for soil sampling and destructive root studies and the remaining 30 m was used to evaluate crop growth (non-destructive), yield and grain/seed. The trial consisted of twelve main plots subdivided into three sub-plots allocated to three tillage treatments, namely: Each main plot was subdivided into four sub-plots allocated to four tillage treatments, namely: continuous no-till (soil left undisturbed until planting and then planted with a tined no-till (NT) planter), non-inversion tillage (deep tine (DT)to a depth of 400 mm) and inversion tillage (soil inverted using a disc- or mouldboard plough(MP)). All straw, chaff and stubble remained on the soil surface and no-grazing was allowed on all tillage treatments.

Three crop rotation systems, medic/wheat/medic/wheat (McWMcW), wheat/lupine/wheat/canola (WLWC) and lupine/wheat/canola/wheat (LWCW) were allocated to main plots replicated four times. The last letter in the sequence represents the crop on the field at the time of data collection.

Table 3.2: Different treatments conducted during study at Langgewens Research Farm in 2014 and 2015

Treatment	Sub-plot size (m^2)	Tillage system	Rotation system	Crop planted in 2014
1	150	NT	McWMcW	Wheat
2	150	NT	LWCW	Wheat
3	150	NT	WLWC	Canola
4	150	MP	McWMcW	Wheat
5	150	MP	LWCW	Wheat
6	150	MP	WLWC	Canola
7	150	DT	McWMcW	Wheat
8	150	DT	LWCW	Wheat
9	150	DT	WLWC	Canola
Treatment	**Sub-plot size (m^2)**	**Tillage system**	**Rotation system**	**Crop planted in 2015**
1	150	NT	WMcWMc	Medic
2	150	NT	WLWC	Canola
3	150	NT	CWLW	Wheat
4	150	MP	WMcWMc	Medic
5	150	MP	WLWC	Canola
6	150	MP	CWLW	Wheat
7	150	DT	WMcWMc	Medic
8	150	DT	WLWC	Canola
9	150	DT	CWLW	Wheat

3.5 Statistical analysis

The experimental design was a randomised complete block design and the treatment design a split-plot design with main factor rotation system and the subplot factor tillage. According to Little & Hills (1978:125) a split-plot principle can be applied to experiments where successive observations are made on the whole units over time (days).

Thus, an analysis of variance (ANOVA) was performed on data using PROC GLM procedure of SAS software Version 9.3 of the SAS System for Windows (SAS Institute, 2012). Shapiro-Wilk test was performed to test for non-normality (Shapiro and Wilk 1965). A Fisher t-test with Least Significant Difference was calculated at the 5% significance level to compare treatment means (Otto and Longnecker, 2001).

3.6 Agronomic practices

Crops were managed according to the best practices as recommended by the Technical Committees of Langgewens. The Technical Committee of Langgewens includes experts of all crop related fields. The experimental gross plot size was 60 m x 5 m of which only 30 m was used for soil sampling and destructive root studies. All tillage treatments (conventional tine treatments and mouldboard treatments) were conducted on 19 May 2014 and 20 May 2014, while planting following on the 21 May 2014. All cropping sequences received one of the three tillage treatments which included continuous no-till, non-inversion tillage (deep tine to a depth of 400mm) and inversion tillage (soil inverted using a disc- or mouldboard plough). Wheat, cultivar SST 027, Canola cultivar Hyola 555TT (2014) and Atomic (2015) was planted, using a no-till Ausplow fitted with knife-openers and press wheels. Wheat and canola were planted at 100 kg seed ha^{-1} and 4 kg seed.ha^{-1} on 30 May 2014 and plots received 25 kg.N.ha^{-1} and 12.5 kg.P.ha^{-1}, band-placed with planting. Fifty days after planting wheat and canola received a 40 kg.N.ha^{-1} top dressing. A broad spectrum herbicide (active ingredient of glyphosate) was applied three days before planting to ensure a weed free seedbed in canola and wheat plots. In an effort to reduce annual ryegrass (Lolium spp), an herbicide containing the active ingredient, trifluralin, was applied during the planting process to wheat plots. Post-emergence weed control in wheat included Rezolve® (pyrasulfotole, bromoxynyl and mephenpyr-diethyl) for broadleaf weed control. Canola plots were sprayed with Kurb® (propyzamide) to control annual grasses and Ulraflow® (atrazine/terbuthylazine) for broadleaf weed control. Insecticide Methosa® (Methomyl) and fungiside Prosper Trio® (Tebuconazole+Triadimenol+Spiroxamine/Tebuconazole) were used for wheat and canola. All crop residues remained on the soil surface as zero-grazing and no baling was practised. All crops were harvested in the second week of November 2014, using a small plot harvester specifically designed for small scale research plots.

In 2015 the same agronomic practices were followed for both wheat and canola as was followed in 2014. The planting date in 2015 was 11 May for both wheat and canola, while the medics was self-regenerating from previous years. All crops (canola and wheat) were harvested on 27 October using a small plot harvester specifically designed for small scale research plots. Medics were harvested by cutting 0.25 x 0.25 m size blocks from treatments.

3.7 Data collection

3.7.1 Soil sampling

Soil was sampled and both chemical and physical soil parameters were determined. Five samples per depth in the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm range were taken, pooled and analysed.

3.7.1.1 Soil Physical Properties

3.7.1.1.1 Particle Size Analysis

Particle size was determined for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm layers for continuous no-till, non-inversion tillage and inversion tillage treatments on all cropping sequences. Particle size analysis samples were taken in May 2015 (after tillage). The pipet-method was used as described in the Methods of Soil Analysis Part 4 (Glendon, 2002). In pre-treating the sample prior to dispersion only the organic matter (OM) was removed by using 35% by volume H_2O_2 solution. The mass loss (base mass) was recorded after OM was removed. Secondly, soil samples were dispersed by adding 10 ml Calgon solution and mechanically stirred for five minutes. Thereafter the clay and silt fractions were washed through a 0.053 mm mesh sieve into a 1 dm^3 sedimentation cylinder. Various fractions were weighed and reported as a percentage of the base soil mass. Results obtained from the particle size analysis were used to group each sample into the textural class using the soil textural triangle (Van der Watt and van Rooyen, 1995).

3.7.1.1.2 Coarse fragment percentage

The coarse fragment percentage was determined within the 0-50 mm, 50-100 mm, 100-200 mm and 300-400 mm depths for all tillage treatments and cropping systems. Samples for coarse fragment percentage determination were taken in May 2015. Due to a dilution effect coarse fragments can greatly decrease the water holding capacity of a soil, and can also contribute to the plant available water by storing water (Poesen and Lavee 1994). Coarse fragments were sampled from 36 experimental plots which included

Glenrosa and Swartland soil forms. Soil samples were air dried and the fine fraction (<2 mm) was separated from the coarse fraction (>2 mm) by pre-crushing in a large mortar and pestle to break up large aggregates. The soil was then sieved through a 2 mm mesh sieve. The coarse fragments that was recovered from the soil sample was weighed and the coarse fragment percentage was determined for each soil sample.

3.7.1.1.3 Infiltration rate (saturated and unsaturated)

The infiltration rate (saturated and unsaturated) measurements were executed in March 2015 (after tillage). Mini Disk Infiltrometers (Model S) from Decagon Devices were used for this measurement. Measurements were taken in duplicate on each experimental plot (*Figure 3.6*). The upper and lower chambers of the infiltrometer were both filled with water. The top chamber controls the suction while the lower chamber contains the volume of water that infiltrates into the soil at a rate determined by the suction selected in the bubble chamber. For measurement of the unsaturated hydraulic conductivity (infiltration rate) the suction was adjusted to 0.5 kPa while for the measurement of the saturated hydraulic conductivity the suction was adjusted to 2 kPa. The infiltration rate was determined by setting the infiltrometer at a constant suction of 0.5 kPa in order for the water to infiltrate through the macro pores as infiltration happens to a large extent through the macro pores of the soil (Hillel, 2003). According to Zhang (1997) a suction of 2 kPa is equal to a tension head of 2 cm. Hydraulic conductivity is defined as "the meters per day of water seeping into the soil under the pull of gravity or under a unit hydraulic gradient." (Principles of Soil and Plant Water Relations by M.B. Kirkham, 2005). This is different than infiltration rate, which is defined as "the meters per unit time of water entering into the soil regardless of the types or values of forces or gradients." The infiltrometer was applied to a smooth spot on the soil surface. If the surface was not smooth, a thin layer of fine silica sand or diatomaceous earth was applied to the area directly underneath the infiltrometer's stainless steel disk. It was of utmost importance to ensure good contact between the soil and the infiltrometer. To make the hydraulic conductivity measurement the starting water volume was recorded. At time zero the infiltrometer was placed on a solid contact surface and the volumes were recorded at regular time intervals (30 seconds) as the water infiltrated. The time interval chosen was based on the suction rate for a sandy loam soil.

All infiltrometer readings were converted to infiltration rate values by using the method and calculations described by Zhang (1997). Software are supplied with the minidisk infiltrometer which assist in the infiltration rate calculations. The reader can also refer to the minidisk infiltrometer instruction manual for a more in depth description of equations and calculations, if desired (Mini Disk Infiltrometer User's Manual, Version 1.3, 2005). Calculations can also be downloaded from Decagon Devices website.

Figure 3.6: Measurement of infiltration rate by use of Mini Disk Infiltometers.

3.7.1.1.4 Aggregate stability

Aggregate stability was determined using the wet sieving method of Kemper and Rosenau (1986). Ten subsamples bulked into one were collected and aggregate stability was determined in 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm layers. Samples for aggregate stability analysis were taken in May 2015 (after tillage). The principle of the wet sieving technique relies on the fact that unstable aggregates will break down more easily than stable aggregates when submerged in water. The analysis was conducted under laboratory conditions by using the Eijkelkamp E-365-08.13 wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Netherlands). To avoid determination of small coarse fragments, 4 grams of macroaggregates (2 mm < aggregates < 2.8 mm) of duplicated samples of each replicate were carefully chosen. In the sieve the aggregates were raised and lowered in distilled water for 3 min ± 10 min using a rubber until all aggregates disintegrated. The remaining aggregates were then raised and lowered in Na $(PO_3)_6$ or NaOH for ± 10 min, depending on the pH of the soil sample, by using a rubber until all aggregates disintegrated. The remaining cans contain the water stable aggregates. Sand particles too big to fit through screen remained behind. Both sets of cans were placed in an oven at 110˚C to allow water to evaporate. The weight of the materials in each can was then determined and thereafter the fraction of water-stable aggregates was calculated as follow (*equation 1*):

Fraction = WSA / (WSA + n-WSA)………………………… (equation 1)

Where:

WSA = water-stable aggregates

n-WSA = non-water-stable aggregates

3.7.1.1.5 Macro-aggregate density

Macro-aggregate density was determined by using the clod method as described by (Grossman and Reinsch 2002). This macro aggregates cannot be called clods because the volume of the macro aggregate shrinks up to 20% which results in wrong bulk densities. Macro-aggregates were sampled in November 2014, five months after tillage. High temperatures prevailed before and during sample taking and therefore macro-aggregates were sampled in a dry state. Undisturbed macro-aggregates were excavated at 100 mm depth increments from profile pits (duplicate clod samples were taken). During sample taking great effort was made to ensure that macro-aggregates are in a natural and undisturbed condition. Macro-aggregates were oven dried for 24 hours at 105˚C and the weight was recorded after drying. There after the macro-aggregates were dipped in paraffin wax (70˚C) for a few seconds after the aggregates has been secured with a thread. The aggregate with the wax (clod + wax) was then air-dried and the weight was again recorded. The sample (aggregate+ wax) was then weighed again after it was completely suspended in water. The density of the macro-aggregate was calculated by using the known density of the water and paraffin wax.

Figure 3.7: Sample macro-aggregates covered with paraffin wax used for bulk density determination

3.7.1.2 Soil chemical properties

3.7.1.2.1 $pH_{(H_2O)}$

The $pH_{(H_2O)}$ were determined for 0-10 mm, 10-20 mm, 20-30 mm and 30-40 mm soil depths after tillage treatments were conducted. Samples were collected in May 2015 (after tillage). After calibrating the pH meter 10 g dried soil (<2 mm) was placed in a glass beaker. De-ionised water was added (25 cm^3) and the contents were rapidly stirred for 5 seconds. A 1:2.5 soil to distilled water ratio was used (Miller and Curtin, 2006). After 50 minutes the contents were again stirred and allowed to stand for 10 minutes. The pH was determined after 30 seconds with the electrodes had been positioned in the contents for 30 seconds.

3.7.1.2.2 $pH_{(KCl)}$

The $pH_{(KCl)}$ were determined for 0-10 mm, 10-20 mm, 20-30 mm and 30-40 mm soil depths after tillage treatments were conducted. Samples were collected in 2015 (after tillage). After calibration of the pH meter 10 gram soil (<2 mm) was placed in a glass beaker. Thereafter 25 cm^3 KCl solution (1 $mol.dm^{-3}$) was added. A 1:2.5 soil to solution ratio was used for measuring (Sonmez et al., 2008). The content was then stirred for 5 seconds and again stirred after 50 minutes. It was then allowed to stand for 10 minutes. The pH was determined after 30 seconds with the electrodes had been positioned in the contents for 30 seconds.

3.7.1.2.3 Electrical Conductivity (EC)

The soluble salt content was determined for 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depth increments after tillage. Samples were collected in May 2015. The soluble salt content was determined by mixing 10 g of soil with 50 ml of distilled water. The sample was then placed in a shaker for 30 minutes. After calibration of the Jenway 4510 meter the EC was determined for all samples.

3.7.1.2.4 Chemical composition (C)

The total C content was determined with the Walkley-Black (1934) method for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depth increments. Samples were taken in May 2015. The Samples were air-dried, ground to pass a 2 mm mesh sieve and analysed by the Elsenburg Soil Testing Laboratory according to methods described in the Handbook of Standard Soil Testing Methods for Advisory Purposes (1990).

3.7.1.2.5 Chemical composition (Ca, Mg, K, Na)

The total Ca, Mg, K and Na content was determined after tillage (May 2015) for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depth increments. Samples were air-dried, ground to pass a 2 mm mesh sieve and analysed by the Elsenburg Soil Testing Laboratory according to methods described in the Handbook of Standard Soil Testing Methods for Advisory Purposes (1990). Extractable Ca, Mg, K and Na were determined by the Inductively Coupled Plasma (ICP) analysis of extracts of soil. Results were correlated 1:1 at acid to neutral pH values with exchangeable Ca, Mg, K and Na determined by the ammonium acetate extraction method.

3.7.1.2.6 Chemical composition (Cu, Zn, Mn, B, S)

The total Cu, Zn, Mn, B and S content was determined after tillage (May 2015) for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depth increments. The samples were air-dried, ground to pass a 2 mm mesh sieve and analysed by the Elsenburg Soil Testing Laboratory according to methods described in the Handbook of Standard Soil Testing Methods for Advisory Purposes (1990) (Cu Zn, Mn and B) as well as methods described by the Soil Handbook. Agricultural Laboratory Association of Southern America (ALASA) (2004) (only S). Cu, Zn and Mn were determined by the ICP analysis of extracts of soil in 0.02 M Di-ammonium EDTA soil extracts while B was determined by ICP in hot water soil extracts. Sulphur was determined by ICP in calcium phosphate soil extracts.

3.7.1.2.7 Active C content (Hot water extractable carbon (HWEC))

Hot-water extractable carbon (HWEC) was determined for the 0-100 mm, 100-200 mm, 200-300mm and 300-400 mm soil layers by a modified method of Haynes and Francis (1993). Samples were collected in

June 2014 (before tillage), September 2014 (after tillage) and September 2015 (1 year after tillage). Carbon extraction was conducted by extraction of labile components of soil C at 80 ˚C for 16 hours. Soil samples (3 g oven dry weight) were weighed into 50 ml polypropylene centrifuge tubes. Samples were extracted with 30 ml of distilled water for 30 min on an end-over-end shaker. Thereafter it was centrifuged for 20 min and all the supernatant was filtered through a 0.45 mm membrane filter into separate vials for carbon analysis.

This particular fraction of the SOC was classified as water soluble C (WSC). In the same tubes 30 ml of distilled water was added again to the sediments. Thereafter the tubes were shaken on a vortex shaker for 10 s. This allowed the soil to suspend in the water. The tubes were capped and left in a hot-water bath at 80 ˚C for a period of 16 hours. After the extraction, tubes were shaken for 10 seconds on a vortex shaker. This ensured that the HWEC released from the SOM was fully suspended in the extraction medium. The tubes were then centrifuged for 20 min. The supernatants were filtered through 0.45 mm filters.

The total carbon (inorganic and organic C) for both extracts was determined on a Shimadzu total organic carbon (TOC) analyser model 5000A. The detection chamber was injected with volumes of 40 ml of the extracts for the analysis of total C. Three replicate injections were conducted. The HWEC was the organic fraction of the total extractable C. This fraction was determined by subtracting the inorganic C values from the total hot-water extractable C.

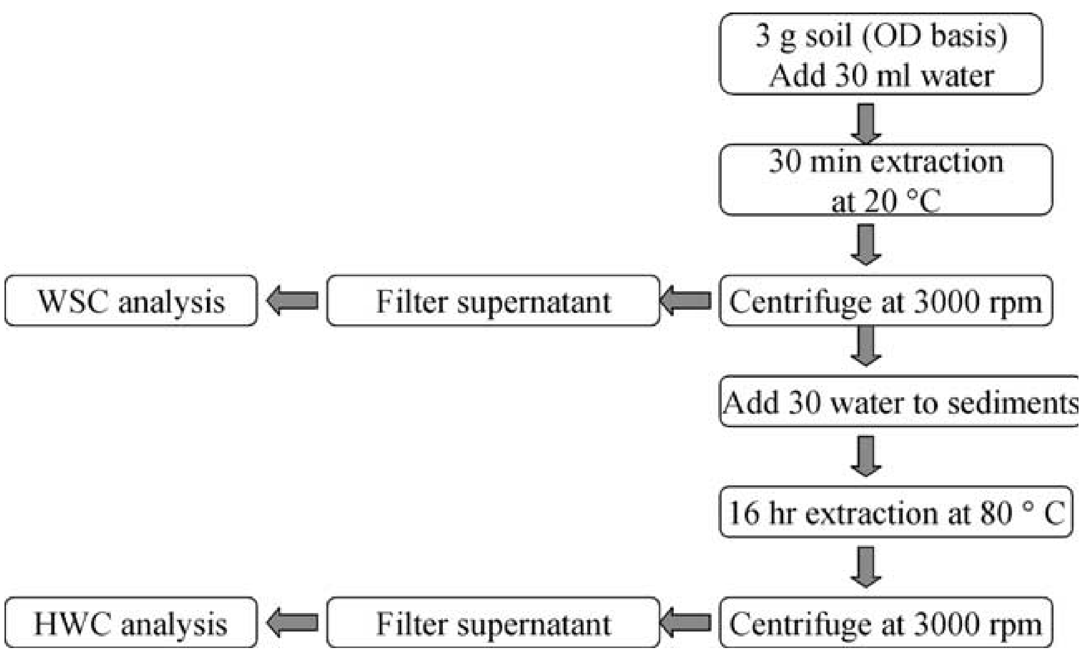


Figure 3.8: Schematic description of procedure for extracting water-soluble (WSC) and hot-water extractable C (HWEC)

3.7.1.3 Soil colour properties

Soil colour was visually measured for the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depth increments using the Munsell colour charts (Munsell Color Company, 1994). Samples were taken in May 2015.

3.7.1.4 Soil water balance (SWB)

3.7.1.4.1 Soil water content (SWC)

In order to determine all the soil water balance parameters the soil water content had to be measured. The Diviner 2000 device was used to monitor soil moisture electromagnetically to a depth of 800 mm through the installation of access tubes (*Figure 3.9*). During the first readings the Diviner 2000 was calibrated at volumetric soil water content at 100 mm depth increments for each experimental site. The Diviner was calibrated in 2012 as part of a previous study on the same soils at the Langgewens Research Farm (Swiegelaar, 2013). Soil water measurements were taken weekly during the growing season (May-November) and monthly during the fallow period (November-April).

Raw data were captured on a logger of the Diviner 2000 for each 10 cm depth increment. Thereafter the data was downloaded onto a PC in a csv file format. Raw data of each soil depth were then used to calculate the total soil water content of the soil and the soil water balance of each treatment by using Microsoft excel.

The installation of access tubes was a difficult and long process due to hard and dry prevailing soil conditions. The tubes were installed in May 2014 after a big rainfall event, but the rainfall event made no contribution towards softening the soil. Due to the hard and dry prevailing soil conditions some access tubes could not be installed to a sufficient depth. During the 2014 growing season 2 tubes were not installed. The exclusion of the two tubes had no effect on the accuracy of data. Tubes were taken out right before harvest in October 2014 and installed again in the same holes right after harvest. Tubes were taken out in 2015 before planting and installed again.

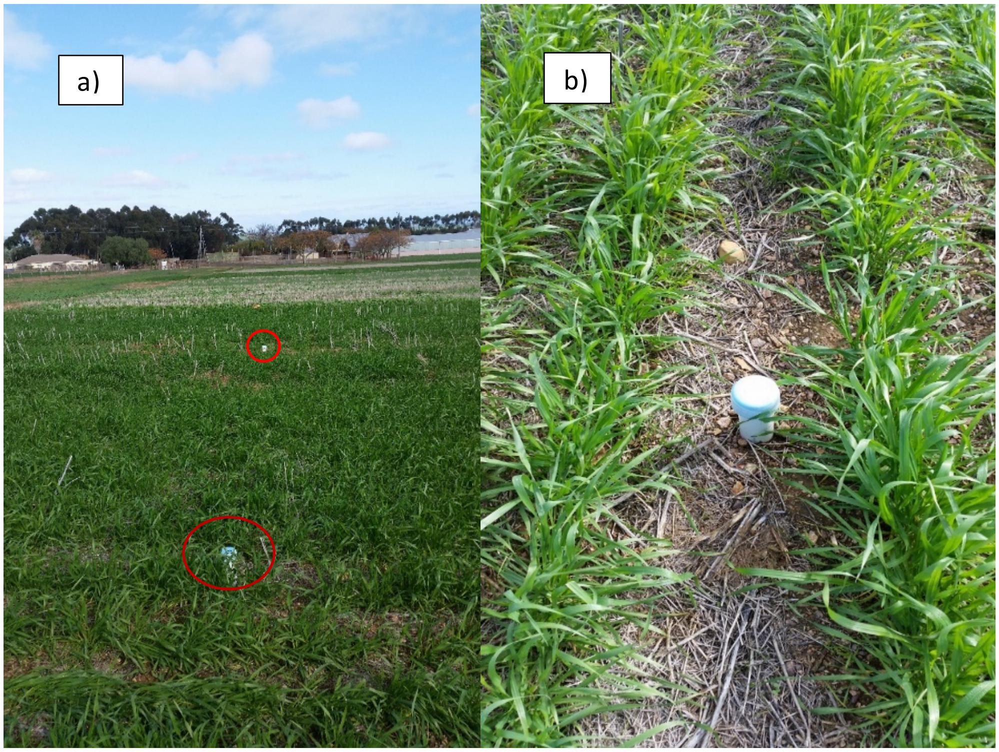


Figure 3.9 (a, b): Installed access tubes for SWC measurement at Langgewens Research Farm 2015

The soil water balance was determined using Hillel's (1998) equation and can be described as:

Change in storage = Gains – Losses

(ΔS+ΔV) = (P+I+U) – (R+D+E+T)……………………………………………………(equation 2)

Where,

ΔS = change in soil water content

ΔV = the amount of water incorporated in the vegetative biomass

P = Precipitation

I = Irrigation

U = Upwards capillary flow into the root zone from a water table

R = Runoff

U = Drainage/deep percolation

E = Evaporation from the soil surface

T = Transpiration by plants

3.7.1.4.2 Evapotranspiration (ET) and Cumulative evapotranspiration (ΣET)

The process of evaporation of water from the soil surface and transpiration is called evapotranspiration (ET). These processes are interlinked and very difficult to measure separately.

The equation can therefore be explained as follow:

(ΔS+ΔV) = (P+I+U) – (R+D+ET), where ET refers to evapotranspiration.

ET and U were calculated for each treatment combination from water balances attached. The water balance was determined by monitoring weekly soil water contents and rainfall events. Thereafter Hillel's (1998) equation (equation 2) was used to determine the soil water balance from which the ET and U was determined. Both the ET and U were calculated using an equation derived from *equation 2*. The assumption was made that runoff (R) was = 0 due to the fact that no runoff occurred during the growing season. The assumption was also made that U was = 0 due to a rainfall event (P) bigger than ΔS at the time which will result in no U as well as a positive ET value. When ΔS is bigger than P, there will be assumed that U do occur, but ET will be = 0.

Therefore the equation for both ET and U is: ET = ΔS + P……………………(equation 3)

3.7.1.5 Crop performance

3.7.1.5.1 Water usage efficiency (WUE)

ET, yield and rainfall parameters were used to calculate the water usage efficiency (WUE) and rainfall usage efficiency (RUE). The WUE was calculated by means of the following equation:

$WUE = \frac{Y}{E+T}$ ………………(equation 4)

where WUE = the water usage efficiency of production per unit evapotranspiration ($kg.ha^{-1}.mm^{-1}$)

Y = total yield ($kg.ha^{-1}$)

E + T = evapotranspiration during the growing season (mm)

3.7.1.4.2 Rainfall usage efficiency (RUE)

The RUE was calculated by means of the equation defined by Hensley, Snyman and Potgieter (1990):

$RUE = \frac{Y}{Rg+Rf-\Delta W}$ ……….(equation 5)

where RUE = the rainfall usage efficiency, namely the production per unit available water ($kg.ha^{-1}.mm^{-1}$)

Y = total yield ($kg.ha^{-1}$)

Rg = rainfall during growing season (mm)

Rf = rainfall during the water gathering period (mm)

ΔW = change in profile water over the potential rooting depth from harvest of the previous crop till harvest of the present crop (mm).

3.8 Crop data collection

A separate study on the crops grown on the treatments included in this study was conducted by Johan Van Zyl, an Agronomy MSc. student. Crop responses will be compared to soil properties included in this study.

Chapter 4: The effect of once-off tillage on selected soil physical and chemical properties

4.1 Introduction

Conservation agriculture (CA) is an important management strategy practiced on many farms in the rain fed crop production areas of the Western Cape (Verster et al., 1992; Meadows, 2004). The beneficial effects of CA on soil properties are well documented (Dick, 1983; Follett and Peterson, 1988; Papendick and Parr, 1997). Soils under CA undergoes less disturbance, are exposed to more diverse root systems and are usually better covered by crop residues. The resultant effect is therefore soil physical and chemical properties that may differ when comparing soil under CA with soil under conventional tillage (CT)

No-tillage (NT) and the accumulation of crop residue at the soil surface results in the conservation of SOC by lowering SOC oxidation, reducing soil temperature, increasing soil water content, macro-aggregate protection and protection against erosion (Golchin et al., 1994; Jastrow et al., 1996; Six et al., 2000; Lampurlanés et al., 2000; Pes et al., 2011). In comparison with CT the continued addition of crop residues to the soil surface combined with minimum soil disturbance enhances biological-, physical- and chemical stabilization and therefore an increase in SOC under NT is expected. SOC in topsoil layers improves hydraulic properties, such as water infiltration, soil water storage capacity, pore stability, soil aggregation, and provides protection against soil compaction (Franzluebbers, 2002; Moreno et al., 2006; Causarano et al., 2008; Tivet et al., 2013).

CT ensures the frequent inversion of soil layers and therefore a uniform distribution of C between soil layers is ensured (Angers et al., 1995; Hernanz et al., 2002). Some studies have shown SOC increases in subsoil layers where crop residues were inverted into deeper layers by tillage (Baker et al., 2006; Blanco-Canqui and Lal, 2008; Olchin et al., 2008). Although, some researchers have come to the conclusion that tillage accelerates the oxidation of organic matter and therefore soils under CT generally tend to contain a smaller amount of C compared to NT (Thomas et al., 2007). Active C is a carbon pool that is easily and quickly lost through tillage, therefore the active C content can be used as a soil quality indicator and will accurately estimate if a tillage practice may tend to result in a C decrease. An increase in active C under NT compared to CT has been reported by several researchers (Leinweber et al., 2001; Balota et al., 2002; Quincke,2006;).

Bare surfaces exposed after the inversion of crop residues are prone to the breakdown of soil aggregates as the energy from raindrops is dissipated which result in the clogging of soil pores, compaction, soil erosion, increased run-off and reduced infiltration. Surface crusting may also take place and form a barrier to plant emergence (P.R. Hobbs, 2006). Numerous researchers reported that soil under NT tend to be more compacted in the upper soil layers compared to soil under CT which may decrease water infiltration dramatically (Martino, 1991; Braim et al., 1992; Lampurlanes, 2001), while others reported no difference in bulk density between CT and NT treatments (Gantzer and Blake, 1989; Hammel, 1989; Lafond, 1993; Ferreras et al., 2000). It must however be kept in mind that factors such as soil texture, aggregation, moisture and organic matter content determines the sensitivity of a soil to compaction (Marshall and Holmes, 1979). Detrimental effects of CA include increased soil bulk densities and soil strength under CA may have detrimental effects on soil water content and root growth (Ehlers et al., 1983; Martino, 1991; Braim et al., 1992). Several researchers concluded that CA leads to the stratification of nutrients in the surface soil layers (Franzluebbers, 2002; Blanco-Canqui et al., 2008; Vu et al., 2009; Deubel et al., 2011; Bell et al., 2012). Drivers for strategic tillage also include the build-up of soil- and stubble-borne diseases (Thomas et al., 1997; Page et al., 2013b), the build-up of herbicide resistant weeds (Felton et al., 1994) and the build-up of insect-pests (Wilson et al., 2013).

Therefore, the new question arising is what the effect will be of once-off tillage (till once in 10 years) of soil that was under long-term CA. According to the SSSA (1997) and Six et al. (2000) one-time tillage of NT soils may have an effect on the stability of soil aggregates, water infiltration, runoff, soil erosion and SOC. Quincke et al. (2007) concluded that one-time mouldboard tillage (MP) did not affect soil aggregation. Pore size distribution for the 2.5 to 10 cm depth was not affected in any way 5 years after one-time ploughing took place on the NT soil (Kettler et al. 2000), however, results are inconsistent and Grandy and Robertson (2006) concluded that fine loamy and coarse loamy NT soils need to be continuously maintained to protect soil aggregation. According to Stockfish et al., (1999) a significant loss of SOC can be expected with one-time tillage of NT soil. Studies conducted by Van den Bygaart and Kay, (2004) concluded that no loss of SOC resulted after one-time tillage of NT soil.

Although the positive effect of once-off tillage on no-till soil have been investigated in the past, only a limited number of studies have investigated the effect this tillage operation has on both soil physical and chemical properties. The evaluation of soil bulk density, water infiltration, aggregate stability, carbon- and active carbon content can be an important tool to assess certain effects of soil management systems of cropped fields on soil and crop performance. Abovementioned factors are without exception influenced by the long term effects of different tillage practices (Lampurlanés et al., 2000; Kovac et al., 2005; Quincke et al., 2007b), cropping systems (Deibert et al., 1982; Sayre and Hobbs, 2004) and stubble management (Unger, 1990; Jaipal et al., 2002). The aim of this chapter was to determine the effect once-off tillage of no-till land has on several soil physical and chemical properties and the resultant crop response.

4.2 Soil physical results

4.2.1 Soil texture (particle size distribution)

Soil texture can be defined as the relative ratio of sand: silt: clay (van der Watt and van Rooyen, 1995). Twelve different soil textural classes exist that can be defined according to their ratios of sand, silt and clay (Van der Watt and Van Rooyen, 1995). Particle size composition were determined for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depths under different tillage and crop rotation systems before and after tillage. *Tables 4.1, 4.2, 4.3, 4.4 and 4.5* summarizes the particle size composition of the treatment combinations included in this study after the conduction of tillage treatments. The NT treatment represents the control treatment.

Particle size composition under different tillage and crop rotation systems in the 0-50 mm soil layer after tillage

Particle size composition results for the 0-50 mm soil layers were summarized in *Table 4.1.* In the canola after wheat system the MP treatment contained a significant lower amount of coarse sand compared to the NT treatment (P = 0.0415), while the NT treatment contained a significant higher amount of clay compared to the MP treatment (P = 0.0413). No statistical difference in particle size composition due to treatment combinations were recorded for both the wheat after canola and wheat after medic system (P = 0.05).

Particle size composition under different tillage and crop rotation systems in the 50-100 mm soil layer

Particle size composition results for the 50-100 mm soil layers were summarized in *Table 4.2.* In the canola after wheat system the DT treatment contained a significantly higher amount of fine sand compared to the MP treatment (P = 0.0190). No statistical difference in particle size composition due to treatment combinations were recorded for the wheat after canola system (P = 0.05). In the wheat after medic systems a significant difference was found between NT and DT with the NT treatment resulting in a higher amount of coarse sand for both systems (P = 0.0256) P = 0.0335).

Particle size composition under different tillage and crop rotation systems in the 100-200 mm soil layer after tillage

Particle size composition results for the 100-200 mm soil layers were summarized in *Table 4.3*. In the canola after wheat system the MP treatment resulted in a significantly higher amount of medium coarse sand compared to the DT treatment (P = 0.0291) while the DT treatment resulted in a significantly higher amount of fine sand compared to the NT treatment (P = 0.0278). No significant difference in particle size was found between all tillage treatments in both the wheat after canola and wheat after medic system (P = 0.05).

Particle size composition under different tillage and crop rotation systems in the 200-300 mm soil layer after tillage

Particle size composition results for the 200-300 mm soil layers were summarized in *Table 4.4.* No statistical difference was found in particle size between all tillage treatments and crop rotation systems (P = 0.05).

Particle size composition under different tillage and crop rotation systems in the 300-400 mm soil layer after tillage

Particle size composition results for the 300-400 mm soil layers were summarized in *Table 4.5.* No statistical difference was found in particle size for both the canola after wheat and wheat after medic system (P = 0.05). In the wheat after canola system both MP and DT treatments resulted in a significantly higher amount of fine sand compared to the NT treatment (P = 0.1111).

Table 4.1: Particle size composition under different tillage and crop rotation systems in the 0-50 mm soil layer after tillage at Langgewens (2015)

Particle size (%) for the 0-50 mm soil depth						
Crop rotation	Tillage treatment	Coarse sand: (2 - 0.5 mm)	Medium coarse sand: (0.5 - 0.25 mm)	Fine sand: (0.25 - 0.106 mm)	Silt: (0.05 - 0.002 mm)	Clay: < 0.002 mm
WLWC	NT	13.33 b	4.67 a	50.00 a	13.33 a	18.67 a
	MP	17.50 a	5.25 a	46.75 a	14.50 a	16.00 b
	DT	14.75 ab	6.25 a	52.00 a	12.00 a	17.50 ab
LWCW	NT	18.00 a	5.00 a	50.50 a	11.00 a	15.50 a
	MP	18.33 a	6.67 a	48.33 a	12.00 a	14.67 a
	DT	18.25 a	6.25 a	39.50 a	21.00 a	15.00 a
McWMcW	NT	18.50 a	5.50 a	48.00 a	12.50 a	15.50 a
	MP	18.25 a	5.50 a	52.50 a	10.00 a	14.00 a
	DT	16.75 a	5.75 a	51.00 a	12.50 a	14.00 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences.

Table 4.2: Particle size composition under different tillage and crop rotation systems in the 50-100 mm soil layer after tillage at Langgewens (2015)

Particle size (%) for the 50-100 mm soil depth						
Crop rotation	Tillage treatment	Coarse sand: (2 – 0.5 mm)	Medium coarse sand: (0.5 – 0.25 mm)	Fine sand: (0.25 – 0.106 mm)	Silt: (0.05 – 0.002 mm)	Clay: (< 0.002 mm)
WLWC	NT	15.75 a	8.00 a	46.67 ab	13.33 a	17.33 a
	MP	16.50 a	7.50 a	45.00 b	14.50 a	16.50 a
	DT	14.25 a	5.50 a	50.75 a	12.00 a	17.50 a
LWCW	NT	15.75 a	6.25 a	48.00 a	12.00 a	16.00 a
	MP	16.50 a	6.50 a	49.00 a	11.50 a	16.50 a
	DT	15.67 a	5.33 a	48.33 a	14.67 a	16.00 a
McWMcW	NT	21.00 a	5.25 a	46.75 a	11.25 a	15.50 a
	MP	17.50 ab	5.75 a	49.25 a	12.50 a	15.00 a
	DT	16.50 b	6.25 a	48.25 a	14.00 a	15.00 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 4.3: Particle size composition under different tillage and crop rotation systems in the 100-200 mm soil layer after tillage at Langgewens (2015)

Particle size (%) for the 100-200 mm soil depth						
Crop rotation	Tillage treatment	Coarse sand: (2 - 0.5 mm)	Medium coarse sand: (0.5 - 0.25 mm)	Fine sand: (0.25 - 0.106 mm)	Silt: (0.05 - 0.002 mm)	Clay: (< 0.002 mm)
	NT	16.25 a	6.25 ab	42.50 b	17.50 a	17.50 a
WLWC	MP	15.00 a	7.75 a	45.25 ab	14.50 a	17.50 a
	DT	14.25 a	5.25 b	49.50 a	15.50 a	15.50 a
	NT	17.25 a	5.75 a	49.50 a	12.50 a	15.00 a
LWCW	MP	17.00 a	4.75 a	48.25 a	12.50 a	17.50 a
	DT	15.33 a	6.33 a	51.00 a	13.33 a	14.00 a
	NT	15.75 a	6.00 a	47.75 a	13.00 a	15.50 a
McWMcW	MP	16.00 a	5.50 a	51.00 a	14.00 a	13.50 a
	DT	17.00 a	6.00 a	47.00 a	15.00 a	15.00 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 4.4: Particle size composition under different tillage and crop rotation systems in the 200-300 mm soil layer after tillage at Langgewens (2015).

Particle size (%) for the 200-300 mm soil depth						
Crop rotation	Tillage treatment	Coarse sand: (2 - 0.5 mm)	Medium coarse sand: (0.5 - 0.25 mm)	Fine sand: (0.25 - 0.106 mm)	Silt: (0.05 - 0.002 mm)	Clay: (< 0.002 mm)
	NT	15.25 a	7.25 a	43.00 a	17.00 a	17.00 a
WLWC	MP	17.25 a	5.25 a	41.50 a	19.00 a	17.00 a
	DT	16.50 a	6.00 a	44.50 a	17.00 a	16.00 a
	NT	18.50 a	5.75 a	44.75 a	15.00 a	16.00 a
LWCW	MP	19.00 a	5.25 a	39.25 a	18.00 a	18.50 a
	DT	16.67 a	5.00 a	47.00 a	15.33 a	16.00 a
	NT	22.75 a	4.75 a	42.00 a	14.50 a	16.00 a
McWMcW	MP	20.00 a	6.50 a	40.50 a	17.50 a	15.50 a
	DT	20.00 a	6.25 a	40.25 a	17.50 a	16.00 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 4.5: Particle size composition under different tillage and crop rotation systems in the 300-400 mm soil layer after tillage at Langgewens (2015).

Particle size (%) for the 300-400 mm soil depth						
Crop rotation	Tillage treatment	Coarse sand: (2 - 0.5 mm)	Medium coarse sand: (0.5 - 0.25 mm)	Fine sand: (0.25 - 0.106 mm)	Silt: (0.05 -0.002 mm)	Clay: (< 0.002 mm)
WLWC	NT	19.75 a	6.00 a	35.75 a	21.50 a	17.00 a
	MP	17.50 a	6.00 a	33.00 a	25.00 a	18.50 a
	DT	18.25 a	6.25 a	39.50 a	21.00 a	15.00 a
LWCW	NT	24.00 a	7.50 a	34.50 b	15.50 a	18.50 a
	MP	18.25 a	6.25 a	45.50 a	14.00 a	16.00 a
	DT	16.00 a	6.00 a	44.67 a	17.33 a	16.00 a
McWMcW	NT	22.50 a	7.25 a	35.75 a	15.50 a	19.00 a
	MP	23.25 a	6.75 a	36.00 a	16.00 a	18.00 a
	DT	22.50 a	6.25 a	34.75 a	17.50 a	19.00 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

All soil layers included in the study were classified as sandy loam soils. For the 0-50 mm, 50-100 mm and 100-200 mm soil layers coarse sand, medium coarse sand and fine sand percentages were added together in order to compare results with results obtained by Botha (2012) and Swiegelaar (2013) who conducted research on the same soils at Langgewens. The results obtained in *Table 4.1, 4.2 and 4.3* do however correlate with results found by Botha (2012) and Swiegelaar (2013) who also found sand percentages of between 50-70 % and clay percentages between 13-20 %.

Even though to a small extent, tillage did have a significant effect on particle size distribution. A long-term study conducted by Lal (1997) in Nigeria proved that tillage practices could result in soil texture changes in the 0-100 mm soil depth. Results from the study showed that no-till mulched plots contained a significantly lower sand content and a significantly higher clay content in the upper 0-100 mm soil layer of no-till mulched plots compared to plough-based un-mulched treatments. Results obtained by Lal (1997) however differ from results obtained during this study as significant differences were only found between MP and NT treatments in particle size distribution in the 0-50 mm soil depth. Due to the fact that the MP tillage action effectively reached a depth of 300 mm the 200-300 mm soil depth was thoroughly investigated to conclude whether the inversion effect of the MP action was visible. As mentioned before, no significant differences were found in particle size between tillage treatments and rotation systems in the latter mentioned depth and therefore it was concluded that the MP treatment had no inversion effect on particle size.

4.2.2 Coarse fragment percentage (%)

The coarse fragment percentage in the soil influences the soil water balance which subsequently influences crop performance through the ability of the soil to store water (Poesen and Lavee, 1994). A higher percentage of coarse fragments leads to a lower actual soil volume and therefore a lower soil water storage capacity. The soil tillage effectively reached a depth of 300 mm for the MP, while the DT soil tillage effectively reached a depth of 400 mm. *Figure 4.1, 4.2 and 4.3* illustrates clearly what happens in soils where coarse fragments are abundant. Coarse fragment percentages were determined for the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depths under different tillage and crop rotation systems. *Figure 4.1*, 4.2 and *4.3* summarizes the coarse fragment percentage of the treatment combinations included in the study.

Wheat after medics in a McWMcW system

Figure 4.1 shows that the coarse fragment concentration increased with soil depth for wheat after medic for both the MP and DT treatments. The NT treatment showed an increasing trend in coarse fragment percentage with depth, although the 100-200 mm soil depth did not correlate with this trend. No significant difference in coarse fragment percentage was observed between tillage treatments at all measured depths (P = 0.05).

Canola after wheat in a WLWC system

Coarse fragment percentages for the WLWC system were summarized in *Figure 4.2.* No clear trend was observed for all tillage treatments at all depths. The highest coarse fragment percentages were recorded in the 300-400 mm soil depth for all treatments. A significant higher coarse fragment percentage was found for the DT treatment compared to both the NT and MP treatments in the 100-200 mm soil depth (P = 0.0020), while no significant difference was found between tillage treatments in the 0-50 mm, 50-100 mm, 200-300 mm and 300-400 mm soil depth (P = 0.05).

Wheat after canola in a LWCW system

Coarse fragment percentages for the LWCW system were summarized in *Figure 4.3*. An increasing trend in coarse fragment percentage was observed for the MP treatment to a depth of 300 mm where after a decrease was observed in the 300-400 mm soil depth. No clear trend was observed for the NT and DT treatments, although higher coarse fragment percentages was observed in the 200-300 mm and 300-400 mm soil layer compared to the lower coarse fragment percentage in the 0-50 mm soil layer for all tillage treatments. No significant difference in coarse fragment percentage was observed between all treatments at all measured depths (P = 0.05).

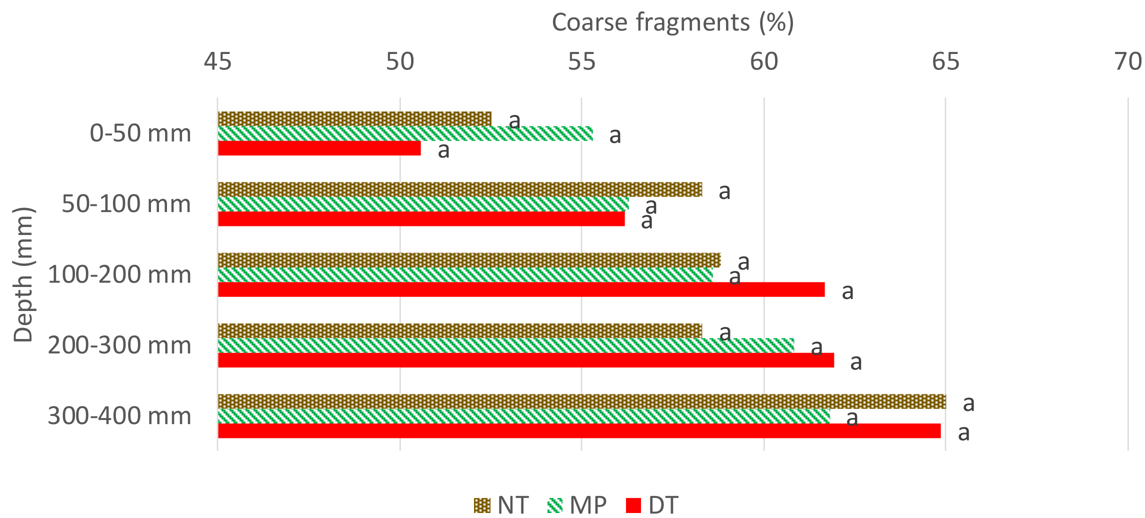


Figure 4.1: The effect of different tillage treatments (NT, MP, DT) on the coarse fragment % under a McWMcW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

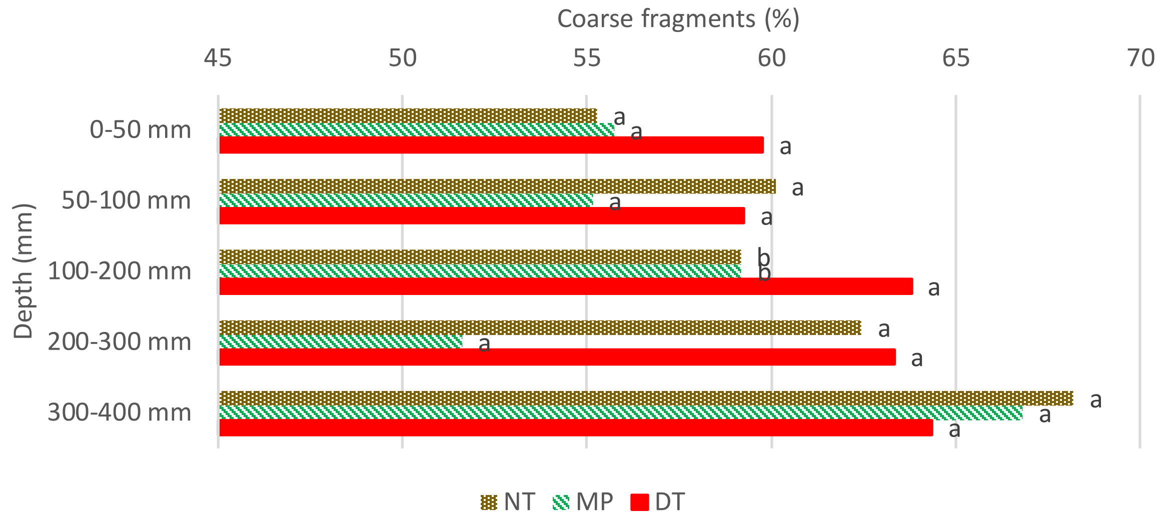


Figure 4.2: The effect of different tillage treatments (NT, MP, DT) on the coarse fragment % under a WLWC crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

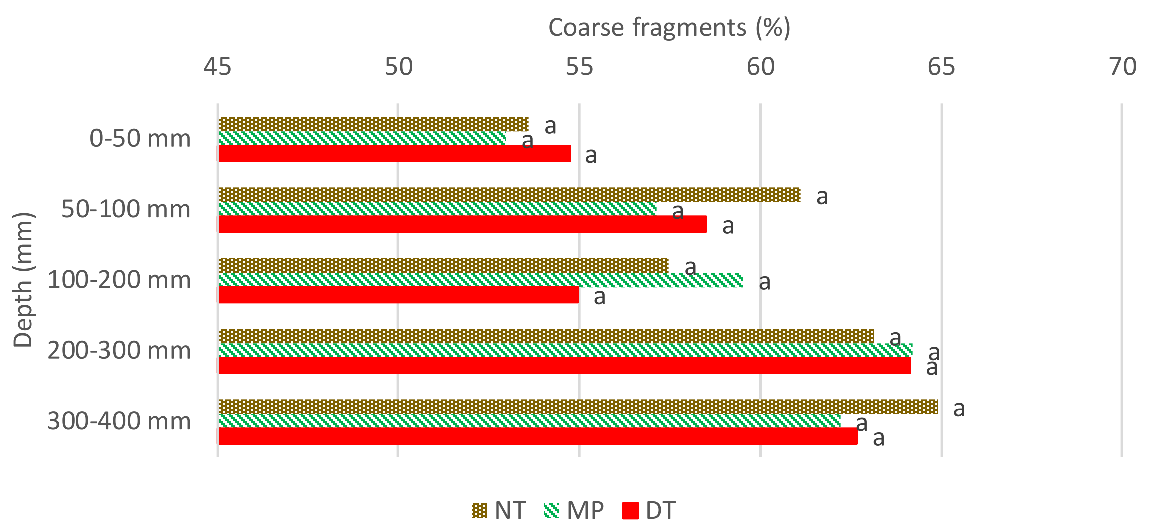


Figure 4.3: The effect of different tillage treatments (NT, MP, DT) on the coarse fragment % under a LWCW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Due to the fact that the soils included in this experiment are very shallow and shale derived a high coarse fragment percentage of mainly shale fragments were expected in the deeper soil layers. This is a common feature of the Malmesbury shales group. The results obtained can however not be compared with results obtained by Swiegelaar (2013) and Botha (2012) also at the Langgewens Research Farm near Moorreesburg. The previously mentioned researchers found that the mechanical sieving action of soil tillage concentrates the coarse fragments in the upper 0-100 mm of the soil and decreases with depth. Similar results to Botha (2012) and Swiegelaar (2013) were also obtained by Oostwoud (1994) and Poessen and Lavee (1994). There must be remembered that tillage was conducted only once after 10 years of NT during the research trials and not annually as was the case with Botha (2012) and Swiegelaar (2013). Therefore, the once-off tillage operation was not able to concentrate the coarse fragments in the upper soil layers. The MP inversion action of soil layers was not observed for any crop rotation system.

4.2.3 Aggregate stability

Figure 4.4, 4.5 and 4.6 contains the aggregate stability % results for treatment combinations included in the study. Statistics were performed for individual systems and depths and compared accordingly.

Wheat after medics in a McWMcW system

Although not significant (Figure 4.4), the highest aggregate stability in the 0-100 mm soil layer was observed for the MP treatment, shortly followed by the NT treatment (P = 0.3226). For both the NT and MP treatments a decreasing trend in aggregate stability was observed with depth, while no clear trend was observed for the DT treatment. In the 100-200 mm (P = 0.0789) and 200-300 mm (P = 0.9967) soil depths no significant difference in aggregate stability were observed.

Wheat after canola in a LWCW system

For all tillage treatments the highest aggregate stability was observed in the 0-100 mm soil depth with aggregate stability percentages ranging between 26-36 % in this particular soil layer (Figure 4.5). In the 0-100 mm soil depth a significant higher aggregate stability was observed for both the NT and MP treatments compared to the DT treatment (P = 0.0078). In the 100-200 mm, 200-300 mm and 300-400 mm soil layers aggregate stability percentages ranged between 13-26 %. No significant differences between tillage treatments were found in the 100-200 mm (P = 0.4992), 200-300 mm (P = 0.5228) and 300-400 mm (P = 0.5716) soil depths. According to West and Post (2002), Lal et al. (1994) and Doran (1987) NT improves aggregate stability in the surface soil layers. Improved aggregate stability under NT is contributed to the greater accumulation of plant residues in the surface layer of the no-till soil (Castro

Filho et al. (2002). For the LWCW system only the DT treatment showed a decrease in aggregate stability with depth while aggregate stability increased with depth from the 100-400 mm soil depth for the NT treatment. No clear trend was observed for the MP treatment.

Canola after wheat in a WLWC system

For all treatments the highest aggregate stability was again observed in the 0-100 mm soil depth (Figure 4.6). Again, although not significantly higher, the highest aggregate stability was observed for NT compared to DT and MP in the 0-100 mm soil depth (P = 0.4098) (West and Post, 2002; Lal et al., 1994; Doran, 1987). A decreasing trend in aggregate stability was observed with soil depth for the DT treatment, while the NT and MP treatments only showed a decreasing trend with depth to a depth of 300 mm where after an increase in aggregate stability was observed. In the 300-400 mm soil depth a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment (P = 0.1514). No significant difference in aggregate stability was observed between tillage treatments in the 100-200 mm (P = 0.7261) and 200-300 mm (P = 0.8135) soil depths.

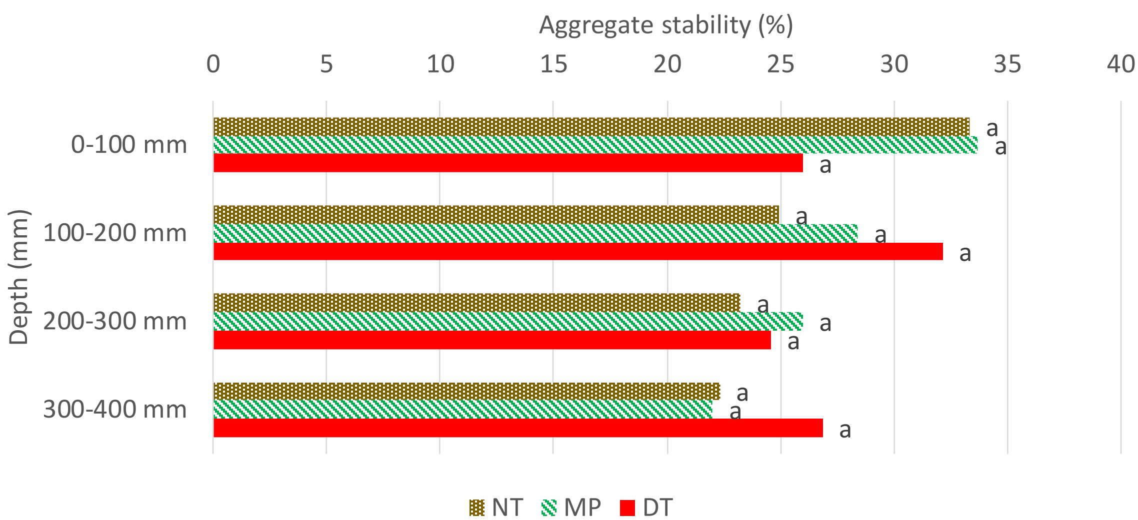


Figure 4.4: The effect of different tillage treatments (NT, MP, DT) on aggregate stability (%) under a McWMcW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

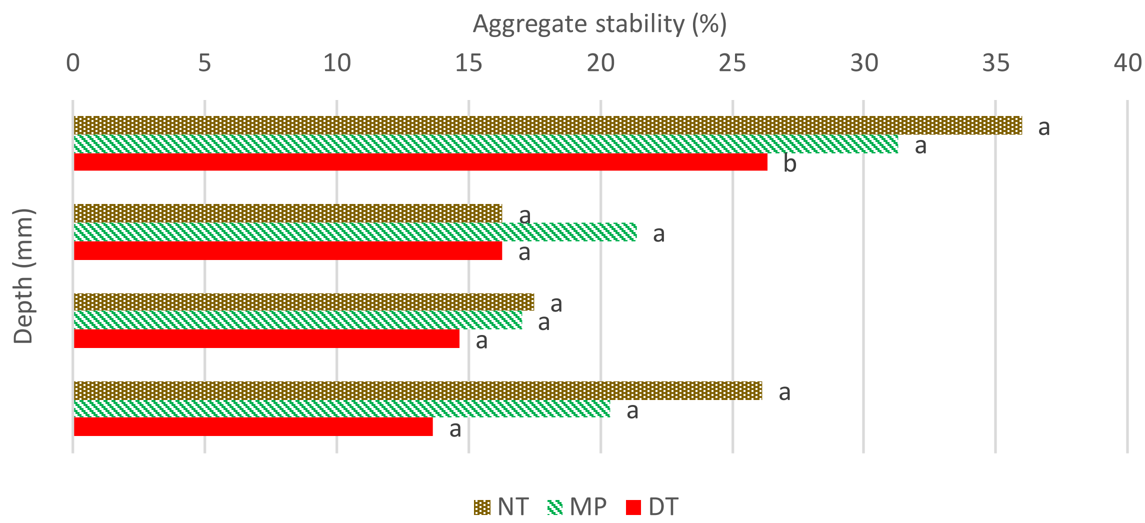


Figure 4.5: The effect of different tillage treatments (NT, MP, DT) on aggregate stability (%) under a WLWC crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

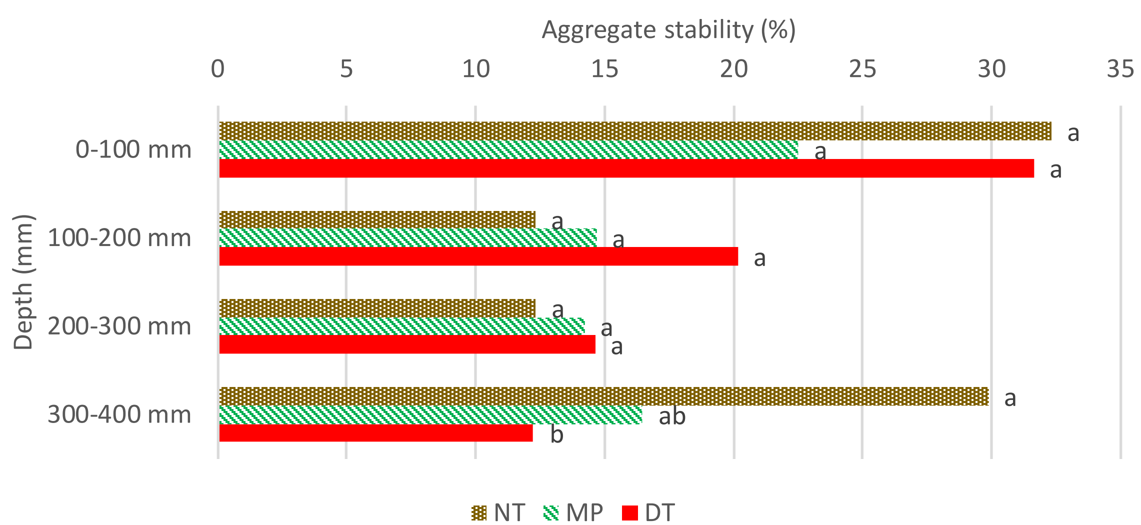


Figure 4.6: The effect of different tillage treatments (NT, MP, DT) on aggregate stability (%) under a LWCW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Several factors can affect aggregate stability in soils and it is important to consider all the contributing factors when interpreting differences in aggregate stability. According to Kölbl & Kögel-Knabner (2004) it is also important to consider increases in clay content as it may lead to increases in aggregate stability. No correlation between clay content and aggregate stability was however found due to no or very small differences in clay content (*Table 4.1, 4.2, 4.3, 4.4, 4.5*) between shallow and deeper soil depths and therefore it was concluded that clay content made no contribution towards aggregate stability.

Aggregate stability results did however correlate with SOC results (*Figure 4.15, 4.16 and 4.17*). The general trend for SOC was a decrease in C content with depth. A similar trend was observed for aggregate stability and therefore it was concluded that the higher C content contributed to the higher aggregate stability in the 0-100 mm soil depth compared to deeper depths. Similar results were obtained by Jastrow et al. (1998) who concluded that a higher C content may result in higher microorganism activity which result in the production of microbial bonding materials for aggregates. The higher C content in the 0-100 mm soil depth was ascribed to the present mulch layer (Thomas et al., 2007; Lal and Bruce, 1999).

When comparing all three crop rotation systems, it was concluded that DT tillage, even though to a very small extent, had a significant effect on aggregate stability. DT tillage resulted in significantly lower aggregate stabilities in both the 0-100 mm soil depth for WLWC and the 300-400 mm soil depth for the LWCW system. This phenomenon may be attributed to the fact that the aggressive mechanical action of the tillage operation was aggressive enough to disrupt the binding-forces between the soil particles and thereby reduce the proportion of water stable aggregates (Kahlon et al. 2013). Results obtained are contradicting with research conducted by Wortmann et al. (2010) who concluded that once-off tillage, with a moldboard plough or a deep-tine implement, had no effect on aggregate stability.

4.2.4 Macro-aggregate density

Due to macro-aggregate shrinkage with a total volume of 25% the macro-aggregate density was determined using the clod method (Grossman & Reinsch, 2002). Macro-aggregate densities were determined for 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depths under different tillage and crop rotation systems. Sample taking occurred in October 2014 (5 months after tillage). Macro-aggregate density results will be compared with previous bulk density research results.

Wheat after canola in a McWMcW system

Macro-aggregate density results for the wheat after medic system (McWMcW) were summarized in *Figure 4.7.* No statistical differences were found between tillage treatments for the 0-100 mm (P = 0.4830), 100-

200 mm (P= 0.3965), 200-300 mm (P = 0.6469) and 300-400 mm (P = 0.0339) soil depths. No significant difference between bulk density results in the 0-100 mm soil layer were also reported by Blevins et al. (1983) who also found no significant difference between CT and NT in the 0-150 mm soil layer in a 10-year tillage corn trial. A similar study conducted in Spain also reported no significant difference between MP and NT in the 0-200 mm soil layer (Pelegrin et al., 1990). For this particular system macro-aggregate densities ranged between 1900-2357 $kg.m^3$. For all treatments, lower macro-aggregate densities were observed in the 100-200 mm and 200-300 mm soil depths, while higher macro-aggregate densities were observed in the 0-100 mm and 300-400 mm soil depths. In the 0-100 mm soil layer the highest macro-aggregate density was obtained for the NT treatment with the DT treatment having the lowest macro-aggregate density. Higher soil bulk densities in surface layers (0-100 mm) compared to deeper soil layers were also observed by Osunbitan et al. (2005), LaFond (1991) and Evertt et al. (1999) who ascribed the phenomenon to particle resettlement after big rainfall events. Higher bulk densities in the 300-400 mm soil layer compared to shallower depths were also measured by Swiegelaar (2013) on the same soils at Langgewens. Swiegelaar contributed high bulk densities in the 300-400 mm soil layer to the presence of a shale layer.

Canola after wheat in a WLWC system

Macro-aggregate density results for the canola after wheat system (WLWC) were summarized in *Figure 4.8*. The highest Macro-aggregate density results were obtained for the NT treatment in the 0-100 mm and the 200-300 mm soil depths. Higher bulk densities under NT in the 0-100 mm soil layer were observed by Osunbitan et al. (2005), Grant and LaFond (1991) and Evertt et al. (1999). When comparing NT and MP, the MP treatments resulted in the lowest macro-aggregate densities in the 0-100 mm, 100-200 mm and 200-300 mm and 300-400 mm soil depths respectively. Results obtained by Alvarez et al. (2009) showed that bulk densities under NT are higher compared to bulk densities under ploughed treatments. In both the 100-200 mm and 300-400 mm soil depths the highest macro-aggregate densities were recorded for the DT treatment. No significant difference between treatments were observed in the 0-100 mm (P = 0.4906), 100-200 mm (P = 0.1083), 200-300 mm (P = 0.4446) soil layers while in the 300-400 mm soil layer a significant higher macro-aggregate density was observed for the DT treatment compared to the MP treatment (P = 0.0004).

Wheat after medics in a LWCW system

Macro-aggregate density results for the wheat after canola system (LWCW) were summarized in *Figure 4.9.* Again the highest macro-aggregate density was obtained in the 0-100 mm soil depth for the NT treatment compared to the MP and DT treatments. Similar results were obtained by Osunbitan et al., (2005), LaFond, (1991) and Evert et al., (1999). A decreasing trend with depth in macro-aggregate density was observed for the NT treatment. For the DT treatment a decrease in macro-aggregate density with depth was observed in the 0-300 mm depth, while an increasing trend was observed for the MP treatment in the 100-400 mm soil depth. No significant differences were however found between tillage treatments in the 0-100 mm (P = 0.2174) (Blevins et al., 1983; Pelegrin et al. (1990), 100-200 mm (P = 0.2559), 200-300 mm (P = 0.2927) and 300-400 mm (P = 0.2610) soil depth.

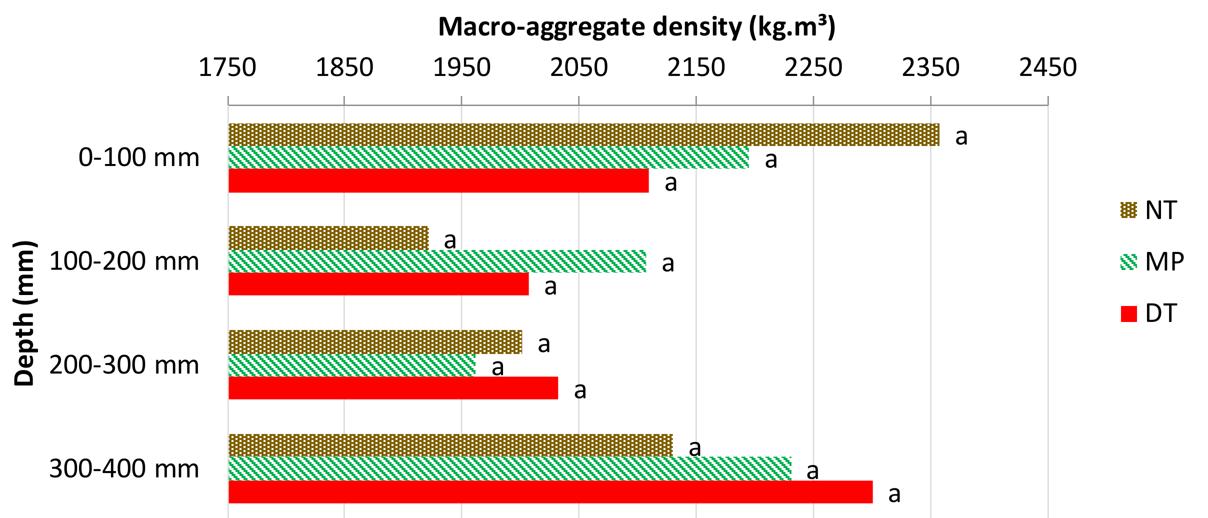


Figure 4.7: The effect of different tillage treatments (NT, MP, DT) on the macro-aggregate density (kg.m^3) under a McWMcW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

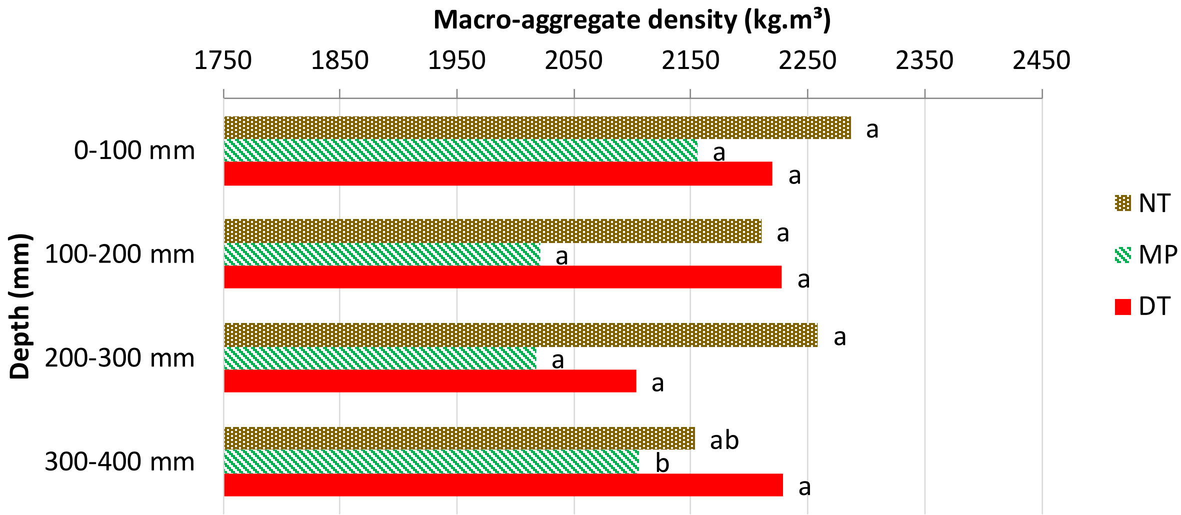


Figure 4.8: The effect of different tillage treatments (NT, MP, DT) on the macro-aggregate density (kg.m³) under a WLWC crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

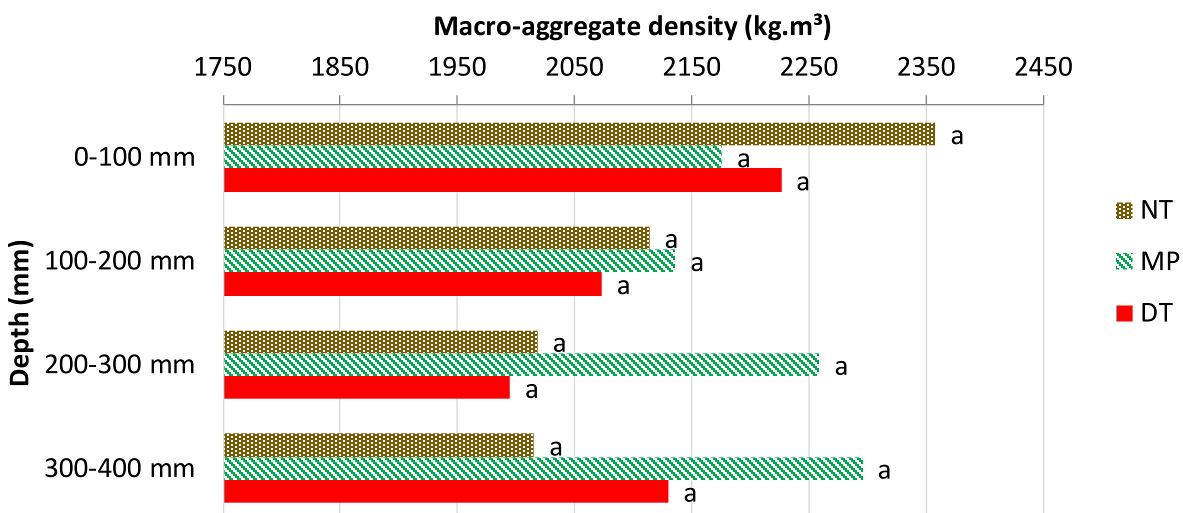


Figure 4.9: The effect of different tillage treatments (NT, MP, DT) on the macro-aggregate density (kg.m³) under a LWCW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Higher macro-aggrgegate densities were generally observed in the 0-100 and 300-400 mm soil layers. Therefore, due to the high macro-aggregate densities in the 0-100 mm soil layer, it was suspected that the A-horizons presented signs of bleaching that can be associated with vesicular crust formation which is a general phenomenon in the Swartland soils (Fey, 2010). Soil colour was therefore determined and it was concluded that the soil surface (0-100 mm layers) for all treatments and crop rotation systems were indeed bleached compared to the deeper soil layers (*Table 4.6*). According to the binomial soil classification system for South African soils a soil is bleached if the colour categorizes in the 10 YR range with a value of 4 and a chroma of 2 or less or a value of 5 and more and a chroma of 3 or less or a value of 6 or more and a chroma equal to 4 (Soil Classification Working Group, 1991). Bleaching can be attributed to a high amount of silicate minerals, especially quartz, which lack coatings of humus and iron oxide. The removal of such coatings occurs through the dispersion of clay and eluviation, podsolization and ferrolysis. Fey (2010) also concluded that the A-horizons of duplex soils often have a weak structure and when it contains a sufficient amount of fine particles (silt and fine sand) it may become hard or very hard in the dry state. This feature is known as 'hard-setting'.

Table 4.6: Soil color measurements for different cropping systems at different depths under different tillage treatments

		McWMcW, WLWC, LWCW
NT	0-100 mm	10 YR 6/4
	100-200 mm	10 YR 6/4
	200-300 mm	10 YR 6/4 or 10 YR 6/3 or 10 YR 4/4
	300-400 mm	10 YR 5/6 or 10 YR 5/4 or 10YR 5/3
MP	0-100 mm	10 YR 6/4
	100-200 mm	10 YR 6/4
	200-300 mm	10 YR 6/4 or 10 YR 6/3 or 10 YR 4/4
	300-400 mm	10 YR 5/6 or 10 YR 5/4 or 10YR 5/3
DT	0-100 mm	10 YR 6/4
	100-200 mm	10 YR 6/4
	200-300 mm	10 YR 6/4 or 10 YR 6/3 or 10 YR 4/4
	300-400 mm	10 YR 5/6 or 10 YR 5/4 or 10YR 5/3

Note: Similar color measurements according to depth were observed for all treatments and crop rotation systems

It must be kept in mind that the macro-aggregate density measurements were taken 5 months after the tillage practices were conducted. Therefore, a change or increase in macro-aggregate density can be expected with time. According to Osunbitan et al. (2003) who conducted research on a loamy sandy soil bulk density increases with time after tillage due to rainfall events and particle resettlement which results in gradual soil compaction. With exception of the significant difference between the NT and DT treatment in the 200-300 mm soil layer for the LWCW system, no significant differences were found between soil depths for all treatments and crop rotation systems (P = 0.05) and it can therefore be concluded that tillage had no effect on macro-aggregate density. Several factors contributed to the fact that tillage had no effect on macro-aggregate density. The first reason was due to macro-aggrgeate density measurements taken 5 months after tillage. Research conducted at the same research farm by Botha (2012) concluded that tillage only has a decreasing effect on bulk density for a time period of 30 days (*Figure 2.2*) on the Langgewens soils, thereafter bulk density values increase and return to values obtained before tillage took place. Differences in macro aggregate stability more likely would have been found if measurements were taken within 30 days of tillage.

The second reason was due to the sampling of undisturbed clods which formed during the breakdown of the soil structure during tillage. Generally, macro-aggrgegate density results for all tillage treatments and crop rotation systems were extensively high. As mentioned before in *Chapter 3, section 3.7.1.4.1*, the soils at Langgewens are very hard, especially in the dry state, and therefore high macro-aggregate densities were expected. Therefore, it was concluded that the soil clods were in an undisturbed form and that the clods were still representative of the NT (before tillage) soil conditions (macro-aggregates).

Clods were scanned via X-ray diffraction in order to investigate an alternative method to determine macro-aggregate density (*Figure 4.10, 4.11*). Promising results were obtained but due to a lack of repetition statistical correlation between clod method and X-ray diffraction could not be drawn. *Figure 4.10 and 4.11* is representative of a clod taken from a LWCW, MP treatment (300-400 mm depth). According to results obtained via X-ray diffraction the macro-aggregate density for the clod in *Figure 4.10 and 4.11* is equal to 2360 $kg.m^3$ while results obtained via the clod method for this particular treatment was equal to 2267 $kg.m^3$. In *Figure 4.10* the light grey objects is representative of the stones present in the sample clod, while the blue and red objects is representative of different pore size volumes. The rest of the clod is representative of the soil. In *Figure 4.11* all the volume of the different pore sizes can be observed and is indicated in different colours according to the colour scale on the left in the figure. The macro-aggregate density via X-ray diffraction was determined by subtracting the total pore volume from the total volume of the sample clod. X-ray diffraction can be considered as a valuable method for determining macro-aggregate density/bulk density in the future.

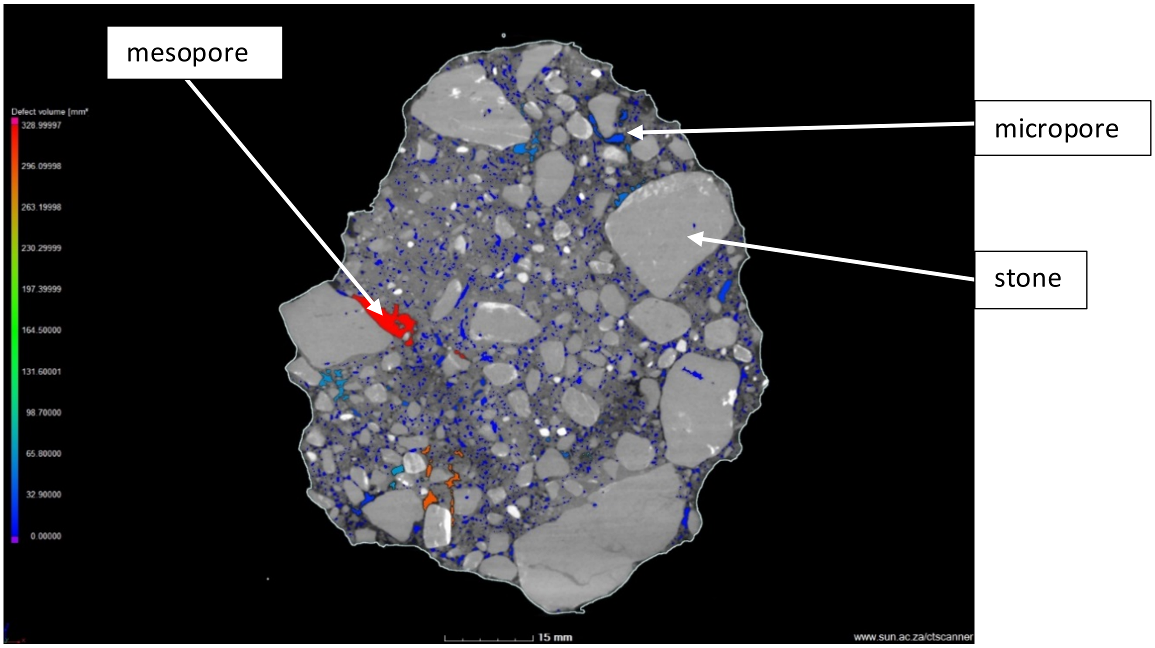


Figure 4.10: Digital image of X-ray diffraction scan of a LWCW, MP treatment (300-400 mm) for bulk density determination at Langgewens 2015 (dark blue represents micropores, red represents mesopores, grey represents soil matrix, lighter grey represents stones)

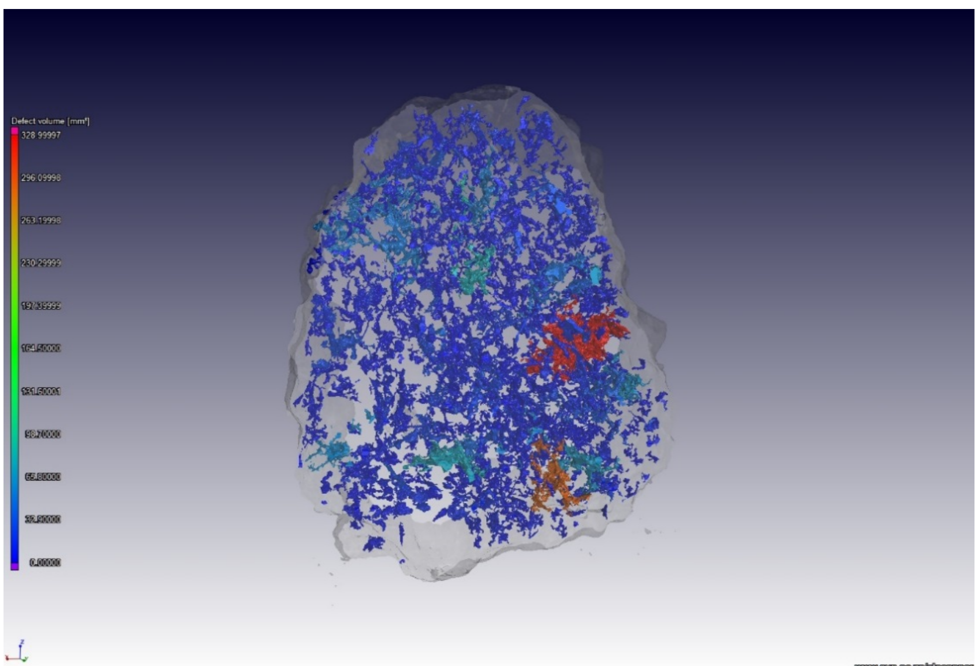


Figure 4.11: Digital image of X-ray diffraction scan of a LWCW, MP treatment (300-400 mm) for bulk density determination at Langgewens 2015 to illustrate pore continuation (dark blue represents micropores, light blue represents mesopores, red represents macropores and grey represents stones)

4.2.4 Infiltration rate (saturated and unsaturated)

The infiltration rate (saturated and unsaturated) measurements were conducted after tillage in March 2015. Mini Disk Infiltrometers (Model S) from Decagon Devices were used for this measurement. Hydraulic conductivity for this particular trial describes the vertical movement of water from the soil surface through the soil profile. Tillage practices which improve hydraulic conductivity may result in higher infiltration rates and therefore increase the soils water holding capacity and decrease run-off and erosion. It was assumed that the conditions under NT would be representative of the conditions before tillage was conducted. It must be kept in mind that infiltration rates were measured a year after the conduction of the first tillage practices (after one growing season). The tillage practices in 2014 was shortly followed by a big rainfall event with a total rainfall amount >39 mm between 27 May-7 June, there after rainfall amounts ranged between 14-27 mm. Therefore, consolidation and particle resettlement under the influence of rainfall took place. Through the inspection of the data it was clear that profiles were fully wetted after rainfall events which caused the weight of the water to contribute to the consolidation of especially the surface of the soil profile. Consolidation of the soil surface was confirmed as high bulk density results were obtained for the 0-100 mm soil depth.

Unsaturated hydraulic conductivity (UHC) (2 kPa)

Although the highest UHC was observed for the DT treatment no significant difference in unsaturated hydraulic conductivity was found between tillage treatments for the canola after wheat system (P = 0.1826) For both the canola after wheat and the wheat after medic systems, the highest unsaturated hydraulic conductivity (UHC) was observed for the DT tillage treatments *(Figure 4.12)*. Similar results were obtained by Thierfelder and Wall (2007) who attributed the higher infiltration rates after ripping to a more favourable soil structure allowing an increase in the capacity for water movement downwards. In the LWCW system a significantly higher unsaturated hydraulic conductivity was observed for the NT treatment compared to both the DT and MP treatments (P = 0.0007). Several researchers concluded that a soils UHC is the highest under a NT system due to the fact that the soils macro-pores, which is formed by earthworms and decayed plant roots, can be preserved under NT, while CT destroys the continuity of the macro-pores (Green et al., 2003; Osunbitan et al., 2005; Thierfelder and Wall, 2007). Roth et al (1992) attributed higher infiltration rates in undisturbed CA soils to greater residue protection compared to unprotected conventionally tilled soils. For all systems the lowest UHC was observed for the MP treatment. MP tillage leaves the soil surface bare therefore lower infiltration rates can be expected due to soil resettlement and the compacting effects of rainfall and runoff over the soil surface (Thierfelder, 2007; Osunbitan et al., 2005; Kribaa et al., 2001). In the McWMcW system a significantly lower UHC was observed for MP compared to the DT and NT treatments (P = 0.1065).

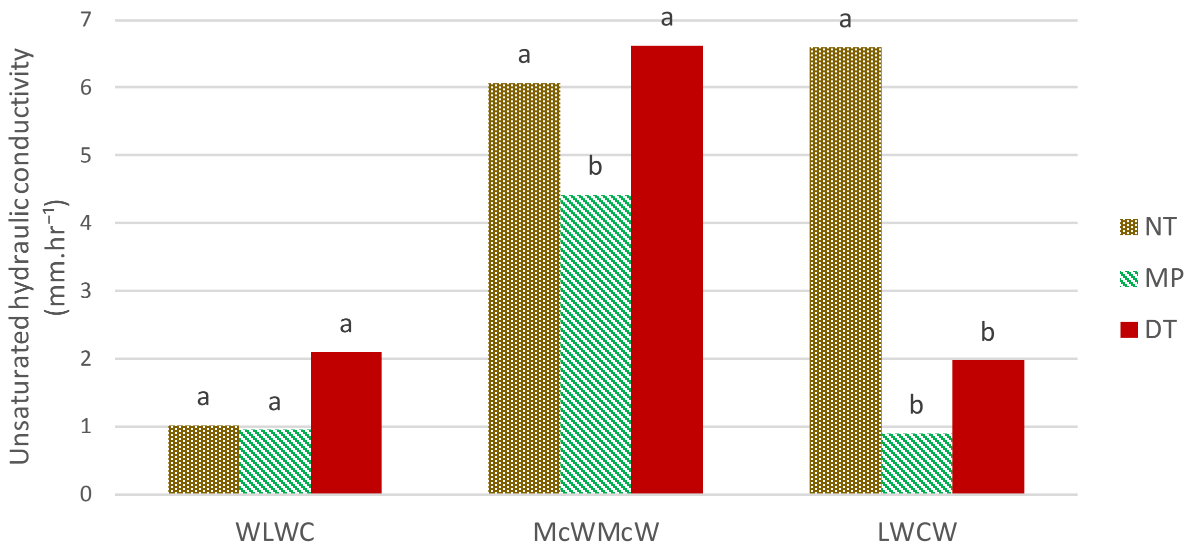


Figure 4.12: The effect of different tillage treatments on the unsaturated hydraulic conductivity (2 kPa) of canola after wheat (LWCW), wheat after medic (McWMcW) and wheat after canola (WLWC) at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Saturated hydraulic conductivity (SHC) (0.5 kPa)

All systems showed the highest SHC for the DT treatment *(Figure 4.13)*. This result can be substantiated by Thierfelder and Wall (2007) who recorded a significantly higher infiltration rate after the application of a rip treatment compared to a ploughed and CA treatment. Both the wheat systems showed the lowest SHC for the MP treatment while the lowest SHC was reached by the NT treatment for the canola after wheat system. For the WLWC system the NT treatment resulted in a significantly lower SHC compared to the MP and DT treatments (P = 0.0041; CV = 18.12289), while the McWMcW system resulted in a significantly higher SHC compared to the NT and MP treatments (P = 0.0037). For the LWCW system the NT treatment had a significantly lower SHC compared to the DT and MP treatments (P = 0.0695; CV = 30.48472).

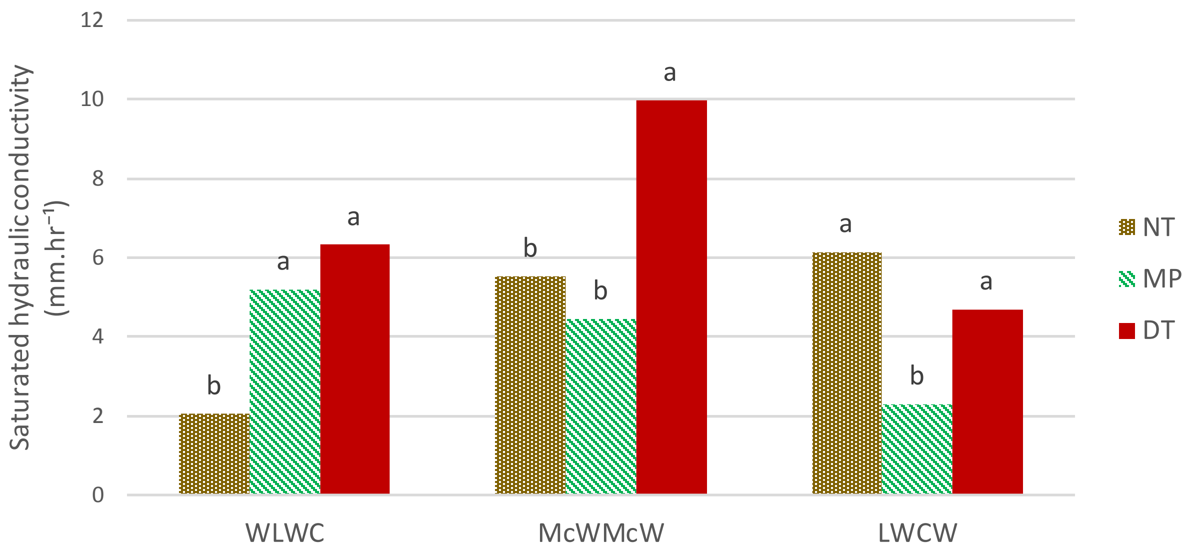


Figure 4.13: The effect of different tillage treatments on the saturated hydraulic conductivity (0.5 kPa) of canola after wheat (WLWC), wheat after medic (McWMcW) and wheat after canola (LWCW) at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

4.3 Soil chemical results

4.3.1 pH (KCl & H_2O)

Table 4.7 contains the pH (H_2O) and pH (KCl) results obtained for different tillage treatments and crop rotation systems at 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depths. pH values ranged between 5.13-5.9 (KCl) and 5.48-6.75 (H_2O) for the wheat after medic system, 4.55-5.60 (KCl) and 5.13-6.50 (H_2O) for the canola after wheat system and between 4.70-5.68 (KCl) and 5.23-6.50 (H_2O) for the wheat after canola system. The values obtained are slightly acidic, which is normal for this type of agricultural soil.

Wheat after medic in a McWMcW system

The highest pH values (in KCl and H_2O) were observed in the 300-400 mm soil layer for all treatments (*Table 4.7*). The lowest pH values (in KCl and H_2O) were observed for the NT and MP treatments in the 100-200 mm soil depth. This trend was however not observed for the DT treatment in the particular mentioned soil depth. NT had a significantly lower pH (H_2O) compared to DT in the 0-50 mm soil depth (P = 0.0235). In the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil layers the lowest pH values (in KCl and H_2O) was observed for NT compared to the MP and DT treatments. Jacobsen and Westerman (1991) similarly observed lower pH values under NT compared to CT systems while Karlen et al. (1991) observed lower pH values under NT compared to ploughed treatments. Soils under NT are frequently more acidic in the surface layers compared to CT systems as a result of an increase in OM and associated organic acids and changes in the proportions of cations and anions in the soil (Logan et al., 1991; Prasad and Power, 1991; Kern and Johnson, 1993; Schomberg, 1994).

Canola after wheat in a WLWC system

Although no significant differences were found in pH (in KCl and H_2O) between all tillage treatments at all measured depths (P = 0.05) for this particular system, the highest pH values were observed in the 300-400 mm soil layer for all treatments, while the lowest pH levels were observed in the 100-200 mm soil layer (*Table 4.7*). MP and NT pH values were closely similar and lower compared to the DT treatment in the 0-50 mm, 50-100 mm, 100-200 mm, 200-300 and 300-400 mm soil depth increments and ranged between 4.65-5.48 (KCl) and 5.13-6.33 (H_2O) for the NT treatment and between 4.55-5.58 (KCl) and 5.13-6.50 (H_2O) for the MP treatment.

Wheat after canola in a LWCW system

The highest pH values were obtained in the 300-400 mm soil layer for all treatments, while the lowest pH values were obtained in the 100-200 mm soil layer for all treatments (*Table 4.7*). No general trend in pH values were observed for all treatments at all depth increments. In the 0-50 mm soil depth a significantly lower pH, in both KCl and H_2O was observed for the MP treatments compared to NT and DT (P = 0.0012 and P = 0.0190 for KCl and H_2O respectively). In the 50-100 mm soil depth a significantly higher pH in H_2O was measured for DT compared to MP (P =0.0092).

Table 4.7: pH values under different tillage and crop rotation systems at different soil depth increments

	Tillage treatment	NT		MP		DT	
	Soil depth (mm)	KCl	H_2O	KCl	H_2O	KCl	H_2O
McWMcW	0-50	5.40 a	5.68 b	5.65 a	5.98 a	5.45 a	5.90 ab
	50-100	5.25 a	5.58 a	5.50 a	5.95 a	5.58 a	5.93 a
	100-200	5.13 a	5.48 a	5.45 a	5.85 a	5.60 a	5.93 a
	200-300	5.35 a	5.93 a	5.73 a	6.18 a	5.55 a	6.08 a
	300-400	5.88 a	6.75 a	5.90 a	6.68 a	5.78 a	6.60 a
WLWC	0-50	5.30 a	5.73 a	5.05 a	5.45 a	5.28 a	5.50 a
	50-100	4.90 a	5.33 a	4.88 a	5.30 a	5.15 a	5.33 a
	100-200	4.65 a	5.13 a	4.55 a	5.13 a	4.88 a	5.23 a
	200-300	4.85 a	5.50 a	4.85 a	5.60 a	5.00 a	5.88 a
	300-400	5.48 a	6.33 a	5.58 a	6.50 a	5.60 a	6.15 a
LWCW	0-50	5.40 a	5.83 a	4.93 b	5.37 b	5.33 a	5.75 a
	50-100	5.15 a	5.55 ab	4.93 a	5.37 b	4.84 a	5.68 a
	100-200	4.75 a	5.23 a	4.83 a	5.33 a	5.20 a	5.65 a
	200-300	4.98 a	5.70 a	5.07 a	5.73 a	5.20 a	5.85 a
	300-400	5.63 a	6.45 a	5.57 a	6.50 a	5.68 a	6.43 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

The general trend observed for all crop rotation systems and tillage treatments were higher pH values in the 300-400 mm soil depth compared to the 0-50 mm, 50-100 mm, 100-200 mm and 200-300 mm soil depth, while the lowest pH values were observed in the 100-300 mm soil depth. The reason for the high pH in the 300-400 mm soil depth can be explained by the presence of a shale layer. Shale derived mother materials generally have a higher pH compared to higher weathered soils (Fey, 2010).

4.3.2 Electrical conductivity (EC)

EC was determined in order to investigate the possibility of the tillage actions resulting in the upward movement of dissolved salts as was found by Botha (2012) on similar soils. Several researchers claimed EC as an important soil quality indicator (Corwin et al., 2006; Fuentes et al., 2009). Because of the pathways of conductance, EC is influenced by a complex interaction of soil properties which includes water content, bulk density, salinity, soil organic matter content and cation exchange capacity (Corwin, 2003; Corwin and Lesch, 2005). EC results obtained are summarized *in Table 4.14, 4.15* and *4.16.*

EC values for wheat after medic in a McWMcW system

For all treatments the highest EC values were obtained in the 0-100 mm and 100-200 mm soil layers while the lowest EC values were obtained in the 200-300 and 300-400 mm soil layers (*Figure 4.14*). The results correlate with results obtained by Fuentes et al. (2009) and Porta et al. (1999) who also measured higher EC values in the 0-200 mm soil layers compared to deeper soil layers. According to Porta et al. (1999) an explanation for the higher EC values in the upper soil layers can be attributed to higher bulk densities in these parts of the soil. This explanation correlates well with bulk density results obtained in *Figure 4.7*. Another explanation for high EC values in the 0-200 mm soil layers can be contributed to the presence of a soil water table during most parts of the growing season in the present shale layer which resulted in the solution of salts in the soil water table. After high evaporation circumstances the soluble salt solution moved upwards towards the soil surface and resulted in the concentration of the salts in the soil surface. EC values ranged between 0.09-0.22 $mS.cm^{-1}$ for the NT treatment, 0.12-0.22 $mS.cm^{-1}$ for the MP treatment and 0.13-0.33 $mS.cm^{-1}$ for the DT treatment. The results obtained in *Figure 4.14* showed no significant difference in EC values in the 0-100 mm (P = 0.3903), 200-300 mm (P = 0.8860) and 300-400 mm (P = 0.2814) soil depths for all tillage treatments. In the 100-200 mm depth the DT treatment had a significantly higher (P = 0.6493) EC value compared to the NT treatment.

EC values for canola after wheat in a WLWC system

For all treatments the highest EC values were obtained in the 0-100 mm and 100-200 mm soil layers while the lowest EC values were obtained in the 200-300 mm and 300-400 mm soil layers (*Figure 4.15*). The results correlate with results obtained by Fuentes et al., (2009) and Porta et al., (1999) who measured higher EC values in the 0-200 mm soil layers compared to deeper soil layers due to high bulk densities. A decreasing trend was observed for the NT, MP and DT treatments with the 0-100 mm depth having the highest EC and the 300-400 mm depth increment having the lowest EC. EC values ranged between 0.07-0.28 $mS.cm^{-1}$ for the NT treatment, 0.06-0.25 $mS.cm^{-1}$ for the MP treatment and 0.12-0.37 $mS.cm^{-1}$ for the DT treatment. Although the highest EC values were measured for the DT treatment and the lowest for the MP treatment at all depth increments, the results obtained in *Figure 4.15* showed no significant difference in EC values between all tillage treatments at 0-100 mm (P = 0.6183), 100-200 mm (P = 0.6525), 200-300 mm (P = 0.7342) and 300-400 mm (P = 0.2400) depth.

EC values for wheat after canola in a LWCW system

For all treatments the highest EC values were obtained in the 0-100 mm and 100-200 mm soil layers while the lowest EC values were obtained in the 200-300 and 300-400 mm soil layers (*Figure 4.16*). As mentioned before, the results correlate with results obtained by Fuentes et al., 2009 and Porta et al., 1999 who measured higher EC values in the 0-20 cm soil layers compared to deeper soil layers due to high bulk densities. Higher bulk densities in the surface layers were measured for the wheat after canola system (*Figure 4.9*). A decreasing trend was observed for the MP and DT treatments with the highest EC values in the 0-100 mm layers and the lowest EC values in the 300-400 mm layers. In the NT treatment only the 100-200 mm layer did not correlate with a decreasing trend. EC values ranged between 0.11-0.24 $mS.cm^{-1}$ for the NT treatment, 0.07-0.20 $mS.cm^{-1}$ for the MP treatment and 0.07-0.36 $mS.cm^{-1}$ for the DT treatment. Although DT had the highest EC in the 0-100 mm layer and MP the highest EC in the 100-200 mm, 200-300 mm and 300-400 mm soil layers the results obtained showed no significant difference in EC values in the 0-100 mm (P = 0.0300), 100-200 mm (P = 0.5396), 200-300 mm (P = 0.6435) and 300-400 (P = 0.2794) mm soil depths for all treatments.

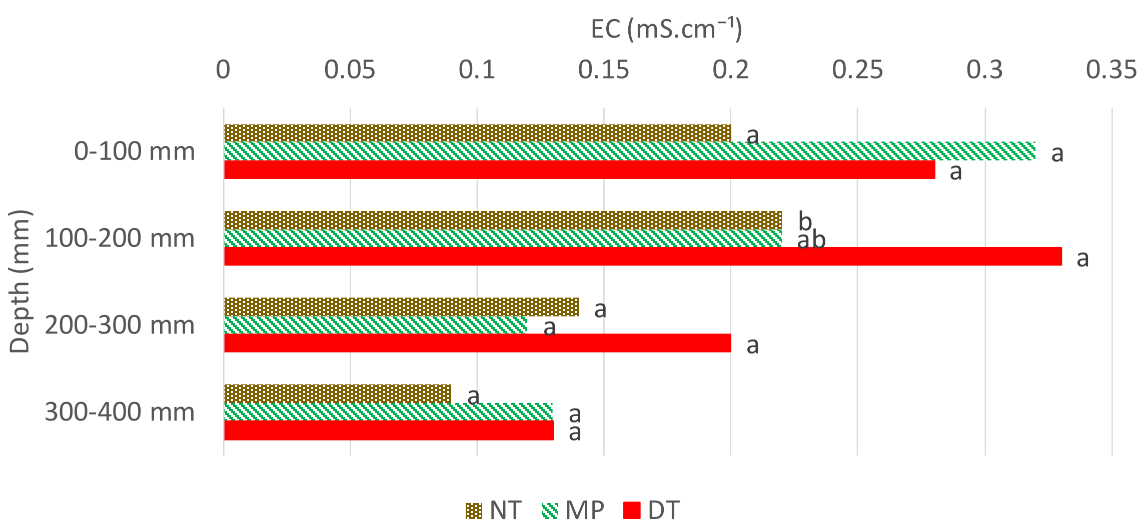


Figure 4.14: The effect of different tillage treatments (NT, MP, DT) on the EC values ($mS.cm^{-1}$) under a McWMcW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

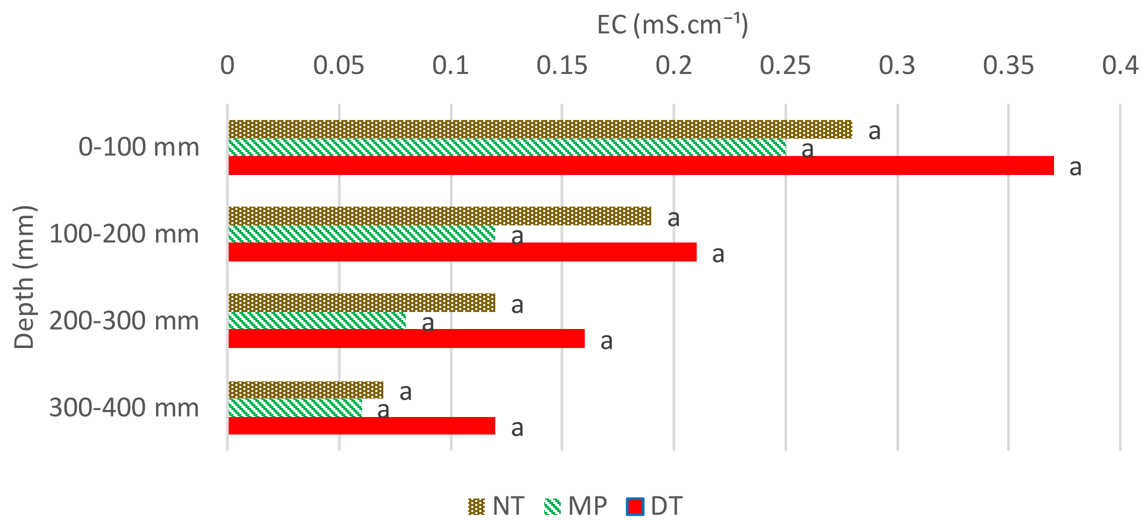


Figure 4.15: The effect of different tillage treatments (NT, MP, DT) on the EC values (mS.cm^{-1}) under a WLWC crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

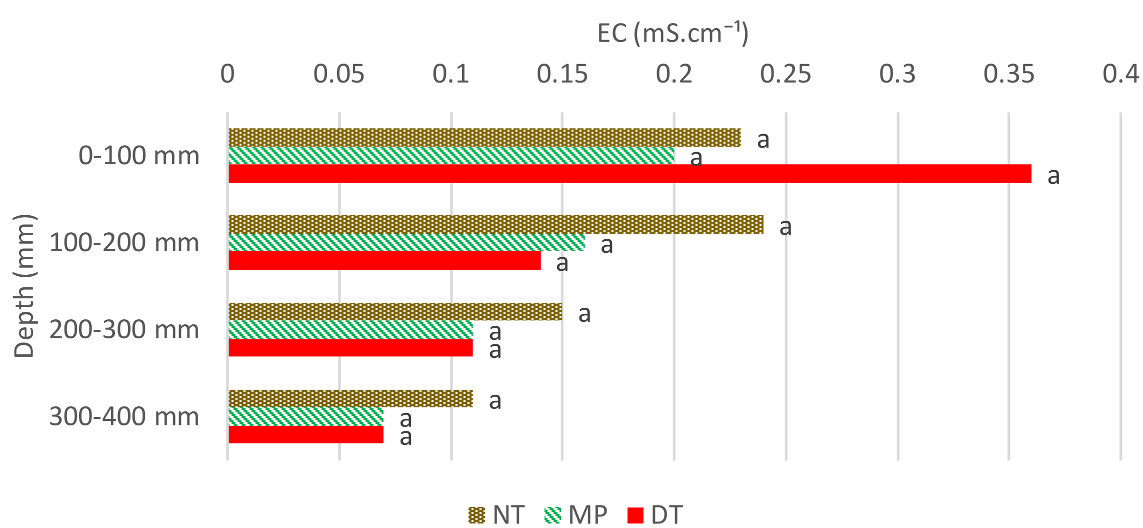


Figure 4.16: The effect of different tillage treatments (NT, MP, DT) on the EC values (mS.cm^{-1}) under a LWCW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

4.3.3 Soil organic carbon (SOC)

SOC results for the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm soil depths for all treatments and crop rotation systems is summarized in *Figure 4.17, 4.18* and *4.19*.

Wheat after medics in a McWMcW system

A decreasing trend in SOC with depth was observed for all treatments (*Figure 4.17*) . No significant difference in SOC content were observed for all treatments at all measured depths (P = 0.05). The DT treatment resulted in a 0.06 $g.kg^{-1}$ higher SOC content compared to MP and 1.69 $g.kg^{-1}$ higher compared to NT in the 0-100 mm soil depth. Similar results were observed by Wortmann et al. (2010) and Vanden Bygaart and Kay (2004). The results however contradict the research of Thomas et al. (2007) and Lal and Bruce (1999) who found a higher amount of SOC closer to the soil surface under NT compared to CT which was attributed to the retention of crop residues at the soil surface. Due to the fact that a higher amount of SOC was observed in the 0-100 mm soil depth compared to deeper depths for all treatments, it was concluded that the influence of the retained crop residues weas still visible. In the 100-200 mm, 200-300 mm and 300-400 mm soil depths higher SOC contents were measured for NT, while the lowest SOC content was measured for DT in the 100-200 mm and 200-300 mm soil depth, and the lowest for MP in the 300-400 mm soil depth (*Figure 4.17*).

Canola after wheat in a WLWC system

A decreasing trend in SOC content with depth was again observed for all treatments (*Figure 4.18*). No significant difference in SOC content was observed for all treatments at all measured depths for this particular system (P = 0.05). In the 0-100 mm soil depth the lowest SOC content was observed for NT, while the highest SOC content was measured for DT. Thomas et al. (2007) and Lal and Bruce (1999) found a higher amount of SOC closer to the soil surface compared to deeper depths under NT which was attributed to the retention of crop residues at the soil surface. In the 100-200 mm, 200-300 mm and 300-400 mm soil depth the NT treatment resulted in the highest SOC content, while no difference in SOC content were observed between NT and DT.

Wheat after canola in a LWCW system

For the wheat after canola system NT resulted in the highest SOC content in the 0-100 mm soil depth while the MP treatment resulted in the lowest SOC content (*Figure 4.19*). Again a decrease in SOC content was observed with depth for all treatments (Thomas et al., 2007; Lal and Bruce, 1999). No clear trend in

SOC content was observed between treatments in the 100-200 mm, 200-300 mm and 300-400 mm soil depth. Again, no significant difference in SOC content was observed for all treatments at all measured depths (P = 0.05).

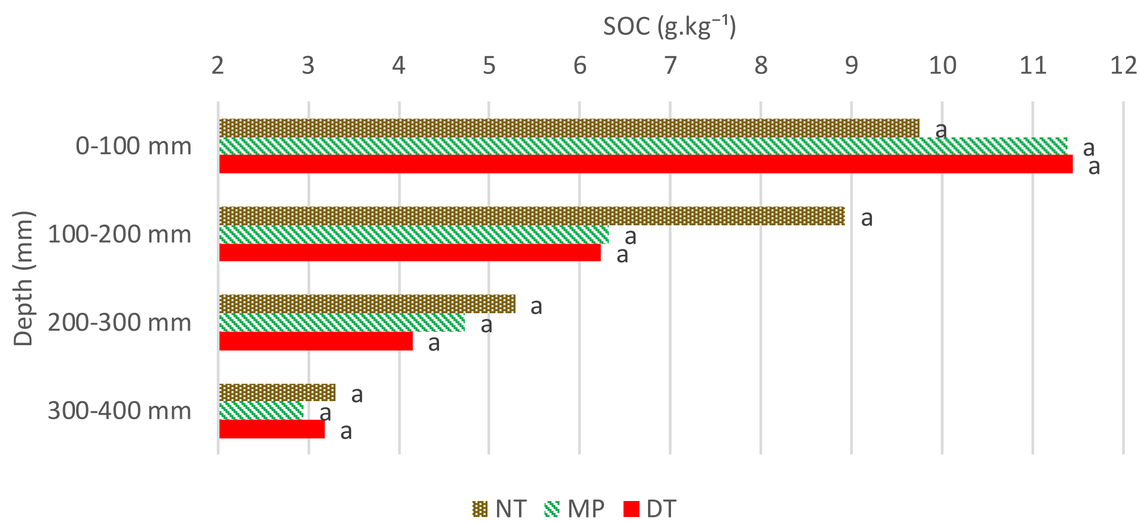


Figure 4.17: The effect of different tillage treatments (NT, MP, DT) on the SOC content ($g.kg^{-1}$) under a McWMcW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

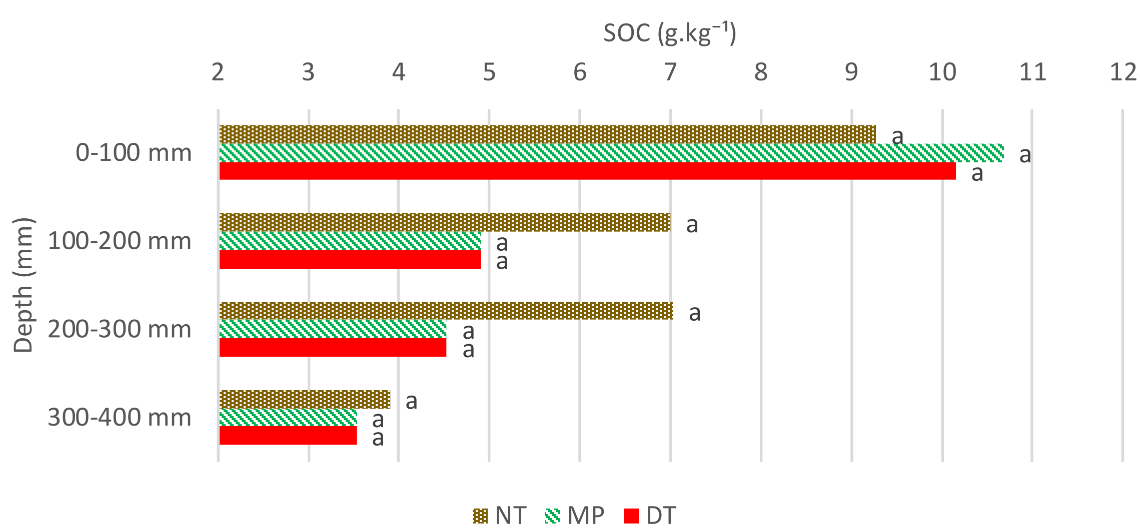


Figure 4.18: The effect of different tillage treatments (NT, MP, DT) on the SOC content ($g.kg^{-1}$) under a WLWC crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

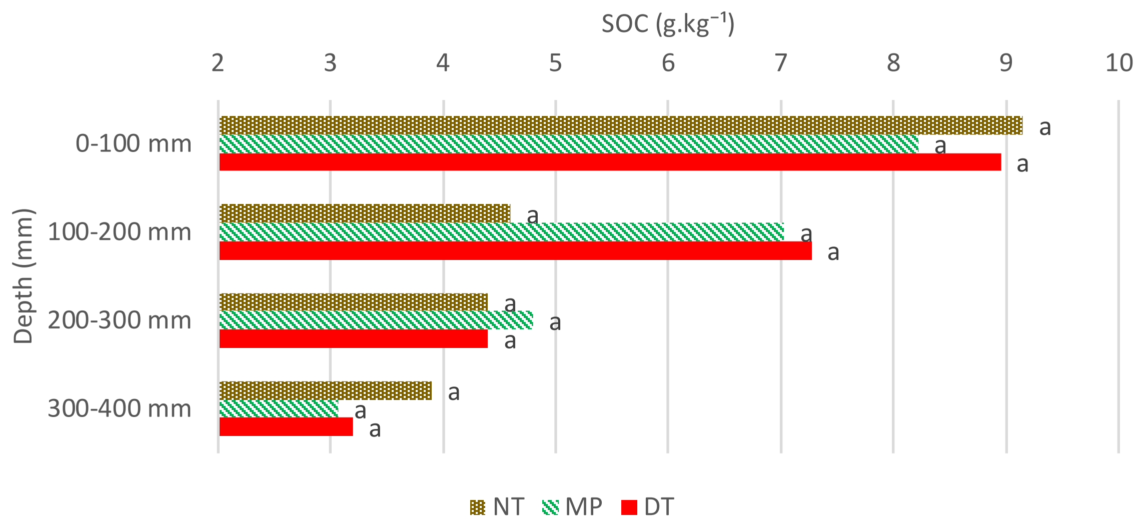


Figure 4.19: The effect of different tillage treatments (NT, MP, DT) on the SOC content (g.kg^{-1}) under a LWCW crop rotation system in the 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm depths at Langgewens 2015

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

When comparing all three crop rotation systems it was clear that the MP treatment did not result in a SOC increase in the 300-400 mm soil depth and therefore it was concluded that the once-off MP treatment did not result in an inversion effect as found by Reicosky (1997) and Quincke et al. (2007). It was concluded that SOC was not affected by once-off tillage in the canola after wheat and the wheat after medic system due to the fact that greater SOC contents were measured in the 0-100 mm soil depth for the MP and DT treatments compared to NT. Similar results were observed by Wortmann et al. (2010) and Vanden Bygaart and Kay (2004).

4.3.4 Active carbon (Hot water extractable carbon (HWEC))

Wheat after medics in a McWMcW (2014)/WMcWMc (2015) system

Before tillage there was no significant difference in active C content between tillage treatments (P = 0.4815)(*Table 4.8*). One year after tillage the active C content for the wheat after medic system was the highest for all treatments when compared to the canola after wheat and wheat after canola system. These results can be supported with results found by Chantigny et al. (1997) who found that the active C content in a clay loam soil was generally higher in the top 200 mm after the addition of a legume specie in the crop rotation system. After the application of a MP treatment the active C content increased with 20 mg/kg, however, after the application of a DT treatment the active C content decreased with 11 mg/kg. Generally, the MP treatment resulted in the highest active C content (417 mg/kg). These results do not correlate with results found by Quincke (2006) who found that labile organic matter pools were reduced by an estimate total of 24-88% in the 0-25 mm depth and increased by an estimate total of 13-81% in the 50-100 mm depth. The NT treatment resulted in the lowest active C content (385 mg/kg). According to results obtained there was no significant difference in active carbon content between different tillage treatments in the McWMcW system after tillage (P = 0.2095)(*Table 4.8*). One year after tillage a significant higher active C content was observed for the DT treatment compared to both the MP and NT treatments (P = 0.0500). After the application of a DT tillage action the soil was exposed to more gas exchange due to an increase in porosity which resulted from the loosening effect of the tine implement and therefore it allowed more microbe activity. As mentioned before, active C is the part of the carbon fraction that is easily available and exposed to microbe conversion, especially under the influence of high temperatures and intensive soil disturbance (Quincke, 2006). Tillage was conducted in May 2014 when soil temperatures and microbe activity were low, therefore the breakdown of organic material was not yet influenced and was active C increases not yet observed. In September 2014 an increase in active C was still not observed due to prevailing low soil temperatures. During the 2014/2015 fallow season and the 2015 growing season high temperatures did however prevail and a greater amount of time followed for microbes to develop and convert the present organic matter and therefore increase the active C content before the next active C sample taking in September 2015 occurred.

Canola after wheat in a WLWC (2014)/CWLW (2015) system

There was no significant difference in active C content between tillage treatments before the conduction of tillage (P = 0.2559)(*Table 4.8*). After tillage the NT treatment (357 mg/kg) resulted in the highest active C content shortly followed by the MP treatment (349 mg/kg). Balota et al. (2002) also came to the conclusion that NT results in higher active C contents when compared to CT. The increase in active C under NT compared to CT was attributed to the lowering of soil temperature due to the presence of surface litter. The accumulation of crop residues at the soil surface provides substrates for soil microorganisms, therefore NT leads to a higher active C content at the soil surface. As for the wheat after medic system, tillage resulted in an increased active C content for the MP treatment (4 mg/kg), and a 5 mg/kg decrease for the DT treatment. No significant difference was found between tillage treatments in the WLWC system after tillage (P = 0.2758)(*Table 4.8*). The highest active C content 1 year after tillage was observed for the

NT treatment while a small difference in active C content were observed for the MP and DT treatments (Balota et al.2002). No significant difference in active carbon content was observed 1 year after tillage between tillage treatments (P = 0.0413).

Wheat after canola in a LWCW (2014)/WLWC (2015) system

No significant difference in active C content between tillage treatments before tillage were observed for this particular system (P = 0.1018)(*Table 4.8*). After tillage the DT treatment showed the highest active C content for the wheat after canola treatment (357 mg/kg) whereas the NT treatment showed the lowest active C content (344 mg/kg). After the application of a MP and DT treatment the active C content increased for both the DT- (13.62 mg/kg) and MP (13.60 mg/kg) treatments. No significant difference was found between tillage treatments in the LWCW system after tillage (P = 0.2499)(*Table 4.8*). The DT treatment resulted in a significantly higher active C content (P = 0.0258) compared to both the MP and NT treatments as for the same reasons as mentioned for the McWMcW/WMcWMc system. The lowest active C content was observed for the NT treatment.

Table 4.8: The effect of different tillage treatments (NT, MP, DT) on the active C content (mg.kg^{-1}) under a McWMcW, WLWC and LWCW crop rotation system in the 0-200 mm depth at Langgewens 2014/2015

		NT	MP	DT
McWMcW/ WMcWMc	Before tillage	381.90 a	433.86 a	322.65 a
	After tillage	385.18 a	417.00 a	386.13 a
	1 Year after tillage	289.96 b	256.95 b	404.79 a
WLWC/ CWLW	Before tillage	350.75 a	322.01 a	348.20 a
	After tillage	357.15 a	349.00 a	339.74 a
	1 Year after tillage	348.57 a	323.60 a	326.05 a
LWCW/ WLWC	Before tillage	332.31 a	342.93 a	355.21 a
	After tillage	343.73 a	356.55 a	368.81 a
	1 Year after tillage	356.82 b	337.96 b	451.71 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

4.4 Conclusion

Significant differences in particle size distribution between tillage treatments at different depths have been found (P = 0.05). Significant differences were most notably found for the coarse and fine sand fraction and between NT and DT treatments. Tillage had no significant effect on coarse fragment % in both wheat systems investigated in the study (P = 0.05), although, in the canola after wheat system the DT treatment resulted in a significant higher coarse fragment percentage in the 200-300 mm soil depth ($P \leq 0.05$). The general coarse fragment percentage trend observed was an increase with depth. This result is however not indicative of a mechanical sieving action which is usually expected after the repeatable conduction of conventional tillage practices.

DT was the only treatment to result in significant aggregate stability decreases in both the WLWC and LWCW crop rotation systems. In the 300-400 mm soil depth (LWCW) a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment (P = 0.0151) while in the 0-100 mm (WLWC) soil depth a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment (P = 0.0078). The aggressive mechanical action of the deep tine implement was responsible for the aggregate stability decrease. Aggregate stability decreased with depth and therefore results correlated with SOC results due to increases in aggregate stability percentages in soil depths where increases in SOC were observed.

With exception of the significant difference between the NT and DT treatment in the 200-300 mm soil layer for the LWCW system, no significant differences in bulk density were found between soil depths for all treatments and crop rotation systems (P = 0.05) and it can therefore be concluded that tillage had no effect on bulk density. Several factors contributed to the fact that tillage had no effect on bulk density. The first reason was due to bulk density measurements taken 5 months after tillage and therefore allowing soil conditions to convert back to initial before tillage soil conditions. The second reason was due to the sampling of undisturbed clods which formed during the breakdown of the soil structure during tillage. Generally, bulk density results for all tillage treatments and crop rotation systems were extensively high. As mentioned before in *Chapter 3, section 3.7.1.4.1*, the soils at Langgewens are very hard, especially in the dry state, and therefore high bulk densities were expected. Therefore, it was concluded that the soil clods were in an undisturbed form and that the clods were still representative of the NT (before tillage) soil conditions.

Although not always significant, both the NT and DT treatments showed the highest hydraulic conductivity compared to MP for all cropping systems investigated (P = 0.05). The increase in hydraulic conductivity for the DT treatment can be explained by a more favourable soil structure created by the rip action, while the increase under NT was contributed to the preservation of soil macro-pores which is formed by earthworms and decayed plant roots as well as the present mulch layer. A MP tillage action leaves a soil surface bare which exposes the soil surface to compacting effects of rainfall and soil resettlement.

MP tillage had a significant effect on pH (KCl and H_2O) while DT tillage had no significant effect. Significant differences were however only observed in the 0-50 mm and 50-100 mm soil depth increments (P = 0.05). The general trend was an increase in pH (KCl and H_2O) with depth and therefore it was concluded that differences were not attributed to a tillage effect but rather to the inherent mother material properties. It is well known that mother materials have higher pH values compared to weathered soil materials. A decreasing trend with soil depth was observed for electrical conductivity. DT proved to be the least favourable in terms of the leaching of salts due to EC increases while NT proved to be the most favourable.

The SOC content was not influenced by the single tillage operation as no significant differences were observed between all tillage treatments at all measured depths (P = 0.05). The highest SOC content was observed in the 0-100 mm soil depth where after SOC decreased with each measured depth. The Active C content was not significantly influenced by a once-off tillage operation as was expected in 2014 (P = 0.0005). The prevailing low soil temperatures did not allow active microorganism activity. In 2015 (1 year after tillage) a significant increase in active C content (P = 0.0258) was observed for DT for both the medic after wheat and the wheat after canola systems which was explained by an increase in microbe activity due to favourable soil conditions.

Chapter 5: The effect of once-off tillage on the soil water balance and the resultant crop response

5.1 Introduction

Conservation agriculture (CA) in the Western Cape Province of South Africa has become a very popular management option for farmers during the past 2-3 decades due to the potential to increase soil productivity compared to conventional tillage (CT) systems. CA is based on the principles of maintaining a permanent soil cover by crop residues or growing crops, avoiding mechanical soil disturbance, and implementing crop rotation (Unger, 1990; Fabrizzi et al., 2004; De Vita et al., 2006). As a result of implementing CA, the sustainable use of agricultural resources can be achieved through the integrated management of water, soil and biological resources (FAO, 2001; Garci' a-Torres et al., 2003). According to Lampurlanés et al. (2000) CA usually increases soil water content by reducing evaporation and runoff, increasing infiltration and thereby increasing crop yield potential. Similar results were obtained by Lal, (1975); Fisher, (1987); Meek et al. (1990); Unger et al. (1991) and Rinaldi et al. (2000). Research conducted by Deibert et al., (1982) on spring wheat on a loamy soil in Minot, North Dakota concluded that the average total soil water at planting and after harvest was higher under a no-till system than was the case with the plough system. The reason for this phenomenon was attributed to the fact that crops under no-till were not using the available soil moisture due to plant roots being concentrated in the upper portion of the profile. Reduced soil disturbance increases microbial activity and results in higher soil organic matter contents which lead to a more stable soil pore system as well as improved aggregate development (Kladviko et al., 1986; Six et al., 2002; (Buschiazzo et al., 1998; Thomas et al., 2007; Unger, 1991; Lipiec et al., 2006; Malumba and Lal, 2008; Blanco-Canqui and Lal, 2007; Keller et al., 2007). An improved soil pore system and soil structure will enable higher water infiltration and will eventually increase yields due to increased available water for crop production (Roth et al., 1988; Shaxson, 2003; Thierfelder et al., 2005; Bhattacharyya et al., 2006; Govaerts et al., 2007; Gruber et al., 2011; Sharma et al., 2011). The maintenance of a permanent soil cover by crop residues resulted in water savings of up to 50 %, (Sayre and Hobbs, 2004). According to Dardanelli et al. (1994) a mulch layer impedes evaporation of water from the soil surface by protecting it from direct solar radiation and air flow across the soil surface leading to higher soil water contents. Unger (1990) reported an 18% increase in rain storage after the soil surface was covered with 10.1 ton wheat residue. De Vita et al. (2007) and Bonfil et al. (1999) found that CA result in both increased water usage efficiency (WUE) as well as grain yield due to minimized evaporative losses from the soil. Thierfelder et al. (2009) found similar results on rainfall usage efficiency (RUE). Higher yields were also attributed to decreased evaporation and increased infiltration.

Results obtained by Thierfelder (2003) have shown that between 10 and 22% of rain water is lost from an uncovered, ploughed soil surface. Water runoff and the resulting soil erosion in conventional agricultural systems is a consequence of limited water infiltration, compacted subsoils and hardpans/reduced macropores (Callebaut, 1985; Lal, 1990). Rockström et al. (2001) compared CA to conventional systems and reported that 10-25% of rain water are lost to runoff and another 30-50% through evaporation due to an uncovered soil surface. Many researchers found that surface soil layers may become more compacted under NT than under CT which can restrict root growth and therefore greatly limit the uptake of water by roots (Ehlers et al., 1983; Hernanz et al., 2001; Meharban Singh Kahlon et al., 2012). According to Godwin (1990) the most important role of tillage in crop development is the effect it has on root development and function. It is the function of the root system to absorb water stored in the soil. This action is only possible if the roots are able to grow into the moist soil before they can access the water.

Stockfish et al., (1999) found that ploughing after 20 years of minimum tillage resulted in a significant loss of organic matter and organic carbon c, but no loss was reported in other studies when organic carbon was measured on an equivalent mass basis (VandenBygaart and Kay, 2004). Infrequent once-off tillage of NT land might provide a solution to effective management of certain perennial weeds by incorporating the weed seeds into the soil (Kettler et al., 2000) and may possibly improve NT over time by burying the soil surface which contains a high soil organic carbon (SOC) and water stable aggregate (WSA) content and bringing less improved soil from deeper parts of the soil to the surface to be improved similarly. WSA were not affected by once-off mouldboard plough (MP) tillage (Quincke et al., 2007b). Quincke et al. (2007b) found that grain yield of grain sorghum (*Sorghum bicolor* L.), corn (*Zea mays* L.), and soybean (*Glycine max* L.) was not affected by once-off tillage. Water infiltration and sorptivity were increased with once-off mouldboard plough (MP) tillage of no-till (NT) soil (Quincke et al., 2007b).

Pagliai et al. (2004) compared MP tilled soil with ripped soil and concluded that the ripped soil resulted in an improved soil pore system by increasing the amount of storage pores as well as elongated transmission pores. The higher macroporosity in ripped soils consequently results in an increased water content and therefore increased plant available water (Pagliai et al., 1995, 1998a).

Although the positive effect of once-off tillage on no-till soil have been investigated in the past, only a limited number of studies have investigated the effect this tillage operation has on the soil water balance.

The soil water balance could be an important tool to assess certain effects of environmental management of cropped fields on soil and crop performance (Hillel, 1998). Calculating the water balance, various soil related parameters such as runoff, drainage/deep percolation and evaporation from the soil surface can be estimated (Hillel, 1998). Abovementioned factors are without exception influenced by the long term effects of different tillage practices (Lampurlanés et al., 2000; Kovac et al., 2005; Quincke et al., 2007b), cropping systems (Deibert et al., 1982; Sayre and Hobbs, 2004) and stubble management (Jaipal et al., 2002; Unger, 1990). It is important to relate management practices to soil water availability for crop production and the resultant water usage efficiency. Using the water balance to evaluate practices that influence soil water will enable the producer to accurately calculate WUE of the crops under consideration as influenced by the treatments tested. The objective of this chapter was to determine the effect once-off tillage of no-till land has on the soil water balance and therefore the resultant crop response.

5.2 Soil water data

5.2.1 Soil water balances for the 2014 growing season

The soil water balance was determined using Hillel's (1998) equation. Hillel's equation is described in detail in *Chapter 3 section 2.7.1.3.2.* Raw water content data of each soil depth and rainfall parameters were used to calculate the soil water balance of each treatment by using Microsoft excel. The water content was electromagnetically measured (Diviner 2000 device) at weekly intervals to a depth of ±800 mm during the 2014 growing season. The 2014 growing season started on 30 May and ended on 27 October. During the first readings the Diviner 2000 was calibrated at volumetric soil water content at 100 mm depth increments for each experimental site. Soil water measurements were taken weekly during the growing season (May-October) and monthly during the fallow period (November-April). Refer to *Chapter 3 section 2.7.1.3* for a detailed explanation of all procedures followed to obtain soil water balance data.

Soil water content (SWC) and cumulative ET (ΣET) are discussed in detail first separately. Thereafter soil water balances are discussed where appropriate on different dates used to examine the most important phenological growth differences during the season, i.e. around 60, 90, 120, 150 and 180 days after planting. In the canola treatments the days after planting represents: flower initiation, full bloom, anthesis going over in pod and seed development, maturity and end of season, respectively. Wheat days after planting indicate the following growth stages: end of tillering, anthesis, end of anthesis and start of dough development, start of maturity and end of season, respectively. The light blue color filled cells indicated the presence of a water table which was estimated through the inspection of water data. Refer to *Figure 3.4* for 2014 rainfall data.

5.2.1.1 Soil water content (SWC)

Refer to *Table 10-19* in *Appendix B* for detailed soil water balance sheets measurements for the 2014 growing season. Refer to *Figure 3.4* for rainfall data.

Wheat after medic in McWMcW

The influence of once-off tillage on the soil water content (mm/800 mm^{-1}) of wheat after medics in the McWMcW system during the 2014 growing season is summarized in *Figure 5.1*. With the exception of 30 July to 13 August (60-73 days after planting) the SWC remained between 150-250 mm for the period 11 June to 10 September. The rainfall recorded in the period 23-30 July (F*igure 3.4)* caused the sharp increase in SWC resulting in the profile to be at field water capacity to a depth of 800 mm. Field water capacity was determined to be equal to 26 mm/100 mm after thorough inspection of data. Similar field water capacity values were determined by Swiegelaar (2013) who also conducted research at Langgewens on similar soils. A sharp decrease in SWC was recorded between 3 September and 15 October (123-135 days after planting) for all tillage treatments tested which was attributed to high evapotranspiration demand of crops reaching maturity and low rainfall. As for the LWCW system the NT system also tended to result in relative higher SWC from 26 June to 3 September (27-94 days after planting) compared to DT and CT. This observation could be the result of relative higher residue cover expected under NT (Unger 1990, Sayre and Hobbs 2004), lower evapotranspiration under NT (Blevins et al. 1979) as well as better water infiltration (Kemper and Derpsch 1981, Fabrizzi et al. 2005). From 13 August to 15 October (103-135 days after planting) the NT treatment contained the lowest SWC compared to the DT and MP treatments which may be contributed to a nitrogen effect from the previous medic crop year. This may be the result of more above ground biomass and subsequent higher transpiration rates which is the dominant component of cumulative ET at that stage (Blevins et al., 1971). With the exception of 30 July where a significant difference was found between MP and NT (P = 0.0101), no significant differences in SWC were found between tillage treatments at all measured dates (P = 0.05).

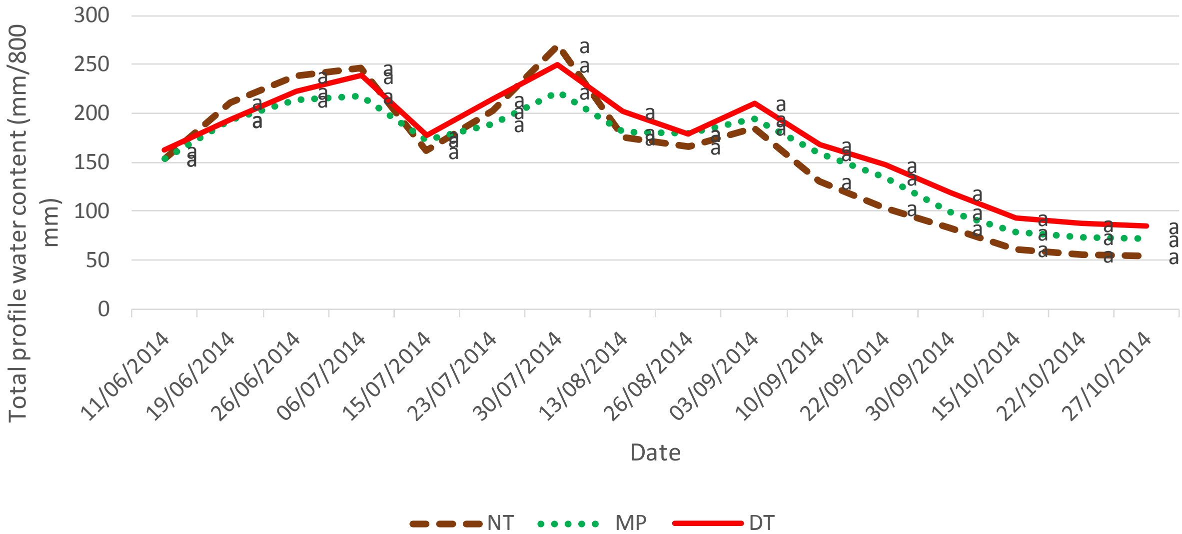


Figure 5.1: The change in SWC of a McWMcW system throughout the 2014 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Canola after wheat in WLWC

The influence of once-off tillage on the soil water content (mm/800 mm^{-1}) of canola after wheat in the WLWC system during the 2014 growing season is summarized in *Figure 5.2.* No definite trend in SWC was observed for the WLWC treatments, although the SWC tended to decrease throughout the growing season for all treatments. From 6 June to 30 July (36-60 days after planting) the DT treatment maintained a SWC between 159 mm-171 mm, where after it decreased until the end of the growing season. Only the NT treatment showed a relevant sharp increase in SWC during the rainfall recorded between 28 May and 4 June (2 days before plant-5 days after plant). This result was again attributed to the higher residue cover and lower evapotranspiration expected under NT (Blevins, 1979; Unger, 1990; Sayre and Hobbs, 2004) and better water infiltration (Kemper and Derpsch 1981, Fabrizzi et al. 2005). An important observation made during data analysis was the presence of a consolidated soil layer in the 200-400 mm soil layer. Only 25% of the total SWC was recorded in the 200 -400 mm layer for the whole growing season, while 75% of the total SWC was recorded in the 0-200 mm soil layer. During the rainfall event which occurred between 21 July and 28 July (52-59 days after planting) all three treatments showed an increase in SWC. The MP treatment maintained a SWC of 106-159 mm between 11 June and 10 September (12-130 days after planting). A sharp decrease in SWC was recorded from 3 September to 15 October (94-135 days after planting) for all treatments which can also be explained by the high evapotranspiration demand of crops reaching maturity and low rainfall during the latter part of the growing season. No significant differences in SWC were found between tillage treatments during the whole growing season (P = 0.05).

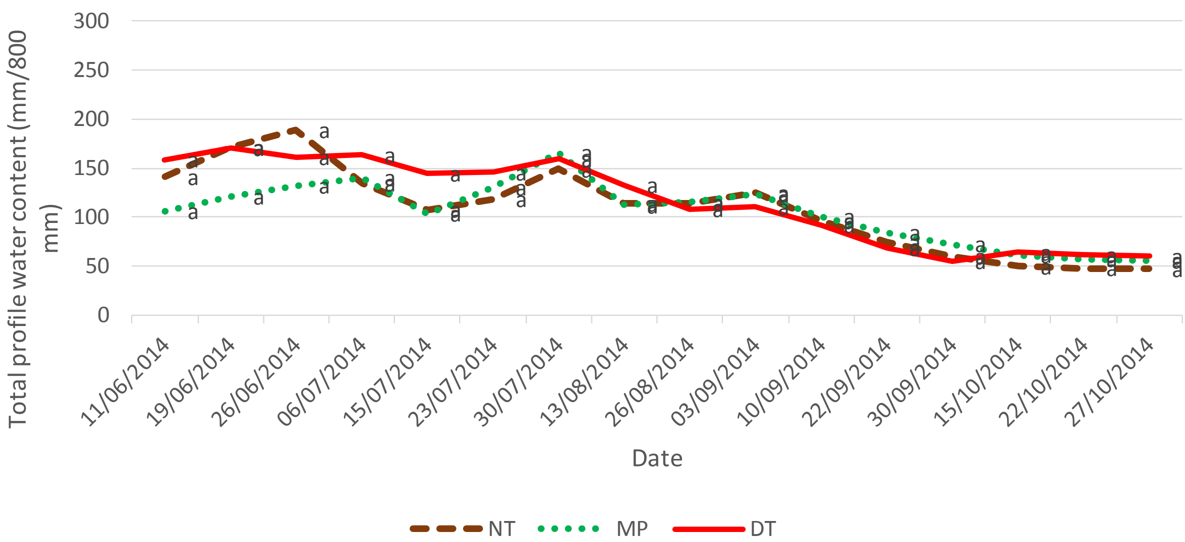


Figure 5.2: The change in SWC of a WLWC system throughout the 2014 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Wheat after canola in LWCW

The influence of once-off tillage on the soil water content (mm/800 mm^{-1}) of wheat after canola in the LWCW system during the 2014 growing season is summarized in *Figure 5.3.* With the exception of 30 July to 13 August (60-73 days after planting) the SWC remained between 100-200 mm from 11 June to 10 September. The rainfall recorded between 23 to 30 July (*Figure 3.4*) caused the sharp increase in SWC resulting in the profile to be at field water capacity to a depth of 800 mm. Field capacity values were estimated through the thorough inspection of water data and similar values were observed by Swiegelaar (2013) on similar soils. A sharp decrease in SWC was recorded between 3 September and 15 October (90-135 days after planting) for all tillage treatments tested. High evapotranspiration demand of crops reaching maturity and low rainfall could have contributed to the rapid decrease in SWC during the latter part of the growing season. NT tended to result in relative higher SWC from 26 June to 3 September (27-123 days after planting) compared to DT and MP. On 26 June NT had a significantly higher SWC compared to DT (P = 0.0139). Between 22 October and 27 October the NT treatment contained a significantly higher

SWC compared to the MP treatment (P = 0.0768) and (P = 0.0106). The higher SWC under NT could be the result of relative higher residue cover (Unger 1990, Sayre and Hobbs 2004), lower evapotranspiration (Blevins et al. 1979) as well as better water infiltration (Kemper and Derpsch 1981, Fabrizzi et al. 2005). Osunbitan et al. (2005) ascribed higher SWC under NT to higher macro-porosity as a result of non-disturbance of root channels and pore spaces created by root growth and soil biological activities from previous years. DT tended to result in the lowest SWC throughout the whole growing season (6 June to 27 October). This observation may have been caused by the aggressive soil loosening action of the DT treatment which caused the water to drain to the deeper soil depths out of reach of the crop roots. The loosening effect was also observed for the MP treatment resulting in this treatment to have the second lowest SWC from 14 June to 14 October 2014 (15-134 days after planting). No significant difference in SWC was found between treatments during the rest of the growing season in the LWCW system (P = 0.05).

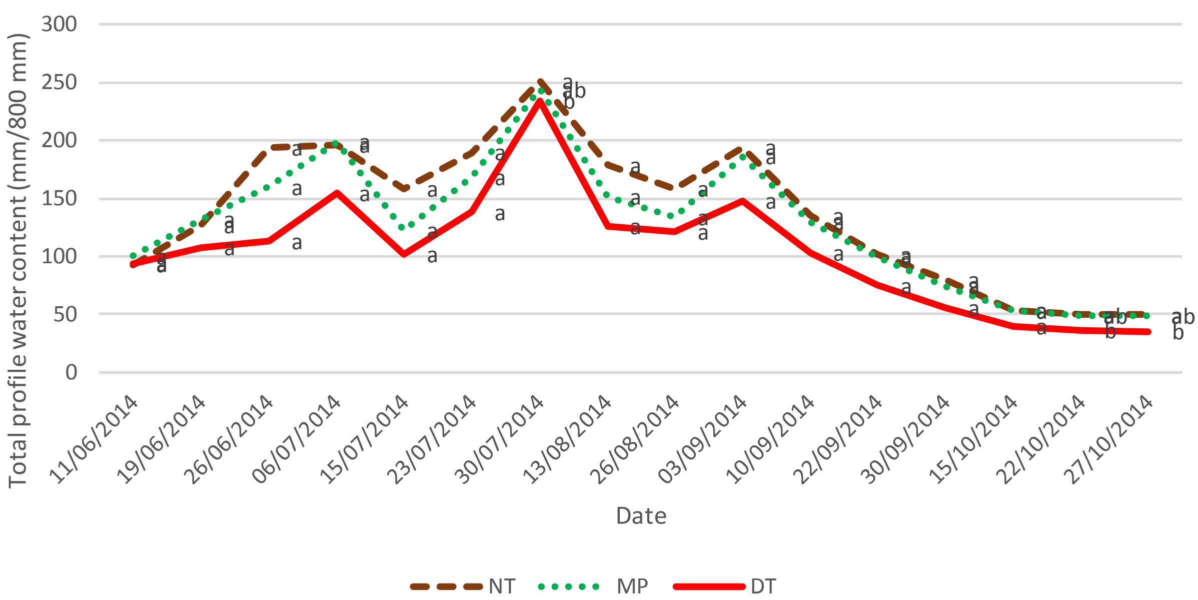


Figure 5.3: The change in SWC of a LWCW system throughout the 2014 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

When comparing all three cropping systems according to their graphs a clear similarity was observed for both the wheat phases. Both the wheat after medic and wheat after canola system maintained the highest water content throughout the growing season when compared to the canola after wheat system. Values between 50-275 mm for the medic after wheat system was achieved, while values between 40-225 mm was achieved for the wheat after canola system. Through thorough inspection of data it was suspected that the higher SWC in 2014 in the wheat after medic system may be attributed to a nitrogen effect from the previous medic crop year. The canola after wheat system maintained water content values between 40-200 mm throughout the growing season. This phenomenon may be explained by the ability of the wheat to capture more water on the ridges compared to the canola. The canola system may have been subjected to more runoff due to the stick-like growth of the canola which is less capable of capturing water when compared to the bush-like growth of the wheat. Both the wheat after canola and the wheat after medic systems showed sharp increases in soil water content after rainfall events, while the canola after wheat showed much lower increases. The NT treatment maintained the highest water content for the wheat after canola system, while the DT treatment maintained the highest water content for the wheat after medic system. A conclusion regarding the treatment resulting in the highest water content for the canola after wheat system could not be made.

5.2.1.2 Soil water content in 100 mm soil depth increments

The soil water content for all treatments in 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm increments were investigated and discussed to determine whether the change in soil water content were attributed to a tillage effect or a crop rotation effect. Refer to *Appendix B*, *Table 10-19* for detailed soil water balance sheets.

SWC for wheat after medics in a McWMcW system

The NT system resulted in the highest SWC throughout most of the growing season in the 0-100 and 100-200 mm soil layers (*Figure 5.4*). The higher SWC may be ascribed to the presence of more organic matter which was a result of N addition from the previous medic crop year. In the 200-300 mm and 300-400 mm soil layers the NT treatment maintained the lowest SWC throughout most part of the growing season. The DT treatment contained the highest SWC at 300-400 mm throughout most part of the growing season. This phenomenon may be attributed to the downwards movement of the soil water to the 300-400 mm soil depth where the presence of the shale layer caused the water to dam up to the 200-300 mm soil layers.

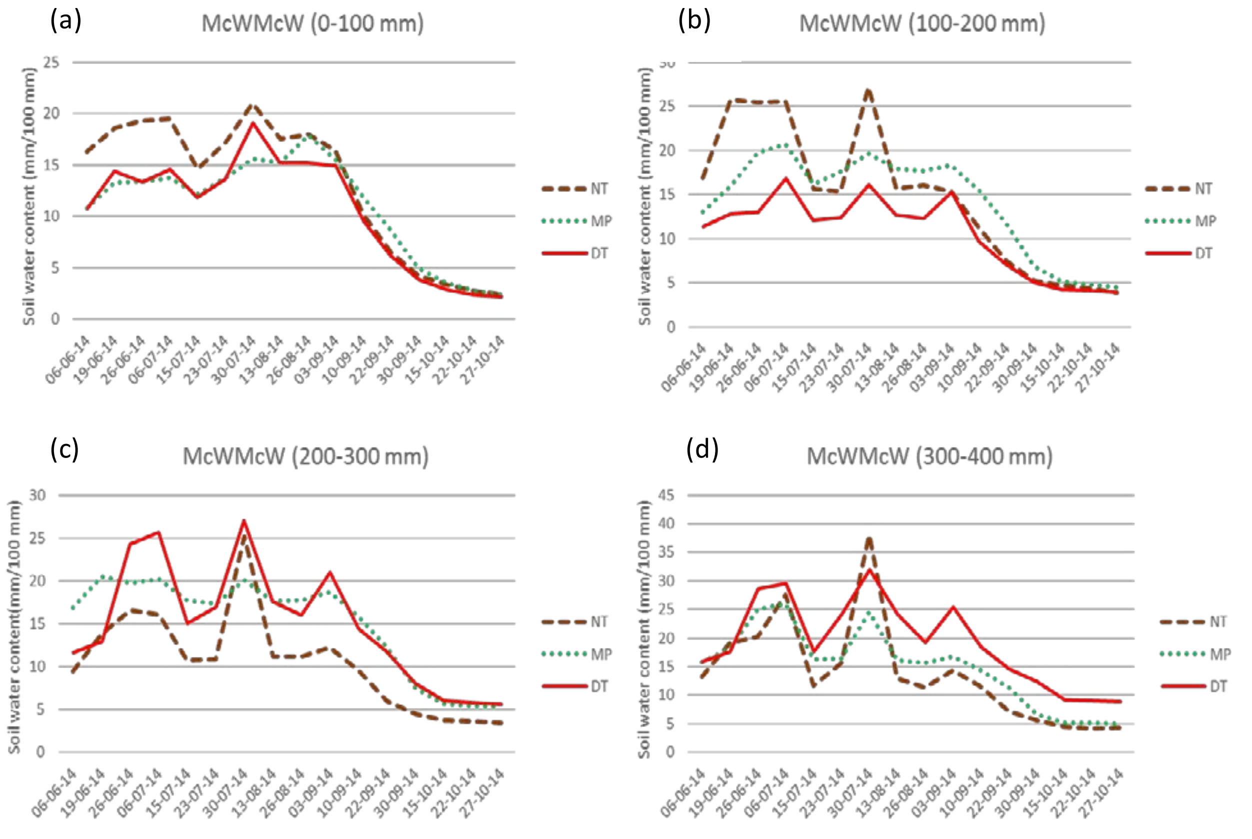


Figure 5.4: The SWC for NT, MP and DT treatments in 100 mm depth increments in a McWMcW system at the Langgewens Research Farm 2014

SWC for canola after wheat system in a WLWC system

The SWC for different tillage treatments in a LWCW system in 100 mm depth increments were summarized in *Figure 5.5.* The loosening effect of the DT treatment caused the water to move down the profile towards the 400 mm soil depth where it started damming up on the shale layer. In the 100-200 mm soil depth the MP treatment resulted in the highest SWC, but in the 200-400 mm soil depth the MP treatment resulted in the lowest SWC. This observation may be explained by the presence of a compaction layer in the 200-300 mm soil layer. Especially in the 300-400 mm soil layer the presence of a compaction layer was clearly observed due to the SWC being lower than 2.5 mm from the beginning of the growing season till end of August (90 days after planting).

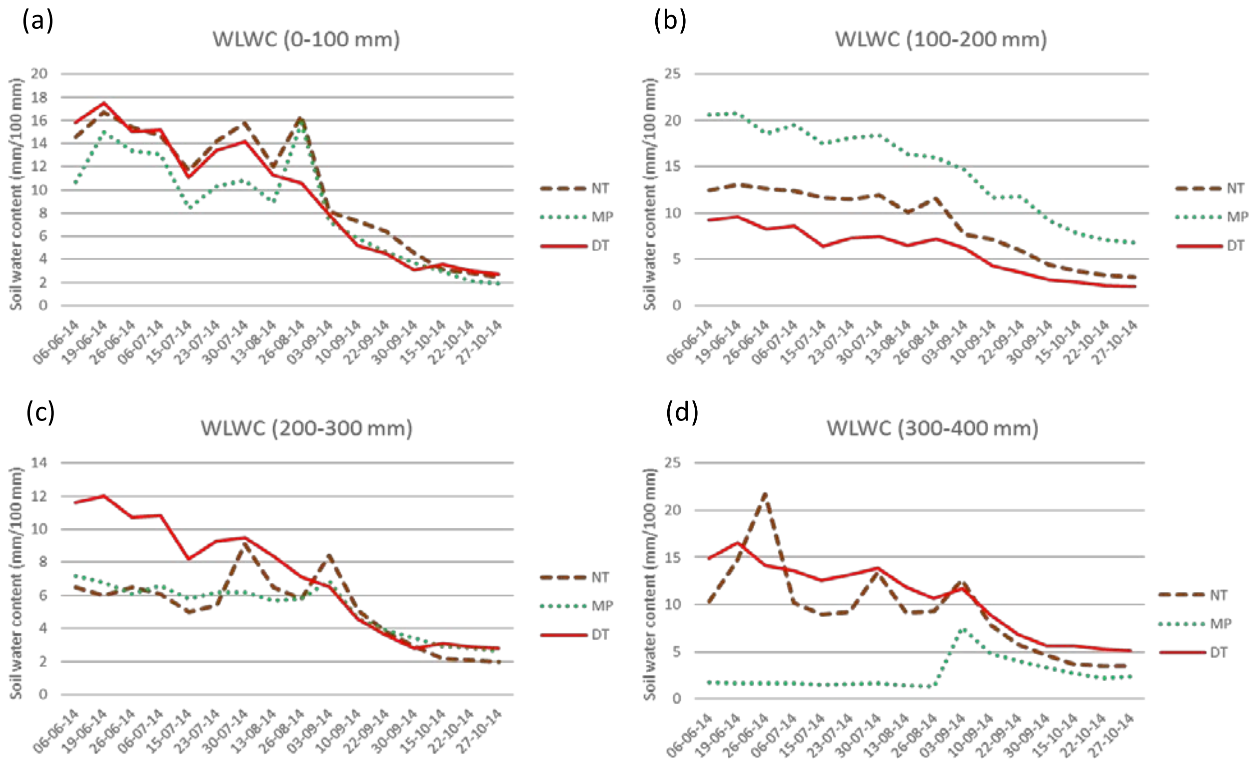


Figure 5.5: The SWC for NT, MP and DT treatments in 100 mm depth increments in a WLWC system at the Langgewens Research Farm 2014

SWC for wheat after canola in a LWCW system

The SWC for different tillage treatments in a LWCW system in 100 mm depth increments were summarized in *Figure 5.6*. In the 0-100 mm soil depth NT resulted in the lowest SWC throughout the whole growing season. It was determined that the more aggressive soil loosening tillage treatments (DT and MP) resulted in higher soil water contents in the 0-100 mm soil depth and this effect was clearly observed until 3 September (94 days after planting). After 3 September no changes in SWC could be seen due to the possibility of soil consolidation after heavy rains. In the 100-200 mm soil depth the DT and MP treatments resulted in the highest SWC due to increased porosities. Soils under conventional tillage (CT) generally have lower bulk density and associated higher total porosity under no tillage (NT) (Lipiec et al., 2006). No clear difference in SWC was observed for the 200-300 mm soil depth. The presence of the porous shale layer at the 300-400 mm soil depth resulted in water damming up from the 400 mm to the 200 mm soil depths.

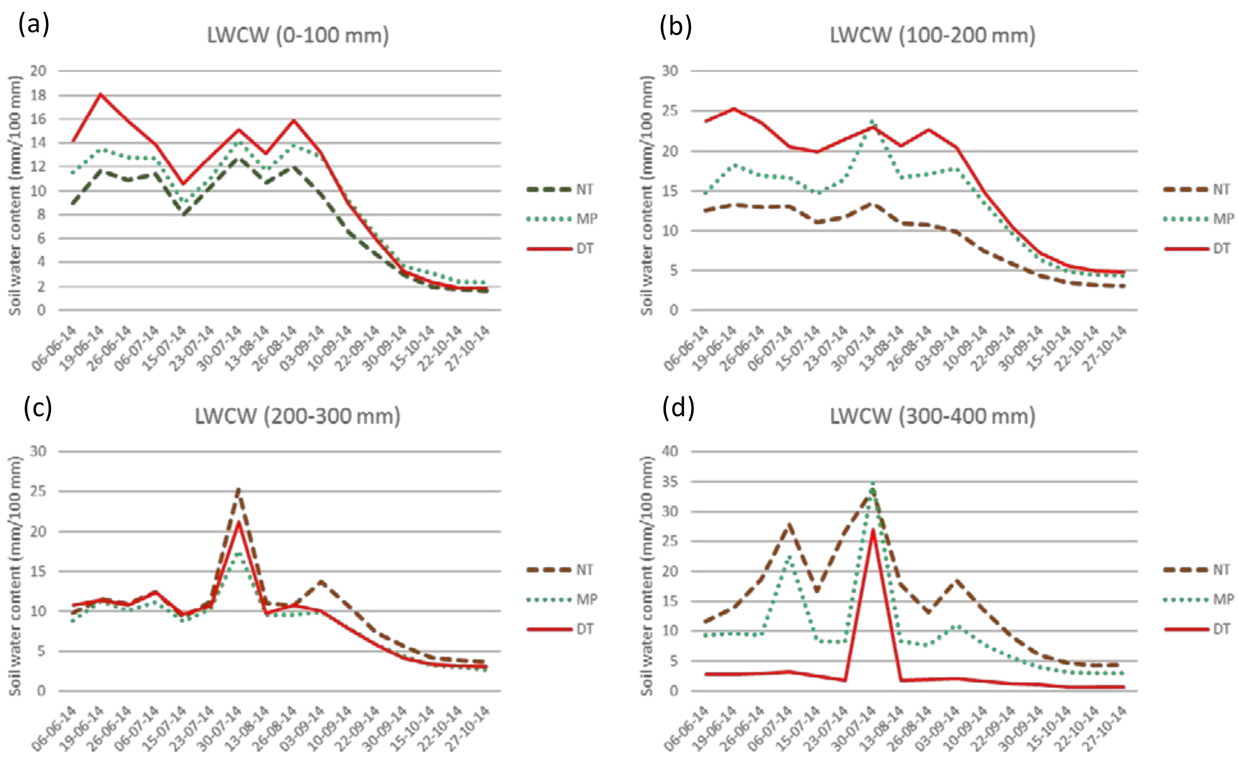


Figure 5.6: The SWC for NT, MP and DT treatments in 100 mm soil depth increments in a LWCW system at the Langgewens Research Farm 2014

When comparing the SWC at different depths for all treatments it was evident that the tillage effect was not long lasting and was only visible till 15 July (45 days after planting). Thereafter the soil was subjected to particle resettlement after periods of rainfall which led to the disappearance of the tillage effects. During drier and warmer periods no differences in SWC were observed for most of the treatments at certain depths.

5.2.1.3 Cumulative evapotranspiration (ΣET) and drainage/deep percolation (U)

ET and U were calculated for each treatment combination from water balances (2014 growing season) attached (*Appendix B*). The water balance was determined by monitoring weekly soil water contents and rainfall events. Thereafter Hillel's (1998) equation *(Equation 2)* was used to determine the soil water balance from which the ET and U was determined. Both the ET and U was determined with *Equation 3*. Refer to *Chapter 3 Section 2.7.3.1.3* for a detailed explanation of the equation.

Wheat after medics in a McWMcW system

The soil water balance calculated for wheat after medics in McWMcW is summarized in *Figure 5.7.* Refer to *Table 10, 11, 12* attached in *Appendix B* for detailed water balance sheets. The same trend in ΣET values were observed for the wheat after medic system as was observed for the wheat after canola system. At the beginning of the growing season (19 June-30 July, 20-60 days after planting) ΣET values ranged between 0 and 86.6 mm with the NT treatment having the highest ΣET at this stage. On 13 August (73 days after planting) the highest ΣET values were obtained for all treatments, where after ΣET values fluctuated according to crop demands and to a much smaller extent the weather. A significantly higher ΣET value was observed for NT compared to both DT and MP ($P = 0.0247$; $CV = 7.905722$). This result correlates with research conducted by Moret et al., (2007) who similarly found higher ΣET values for NT systems compared to CT systems. Moret et al. attributed the higher ET under NT to higher topsoil water contents which enhanced soil water evaporation. ΣET values of 334.2 mm for the DT treatment and 310.9 mm for the MP treatment was obtained at the end of the growing season. The highest drainage amounts occurred under the NT system (83.9 mm), followed by the DT treatment (45.7 mm) and lastly the MP treatment (11.2 mm). This result may be explained by the fact that lateral flow or deep percolation of water from the plots next to the plots under observation occurred.

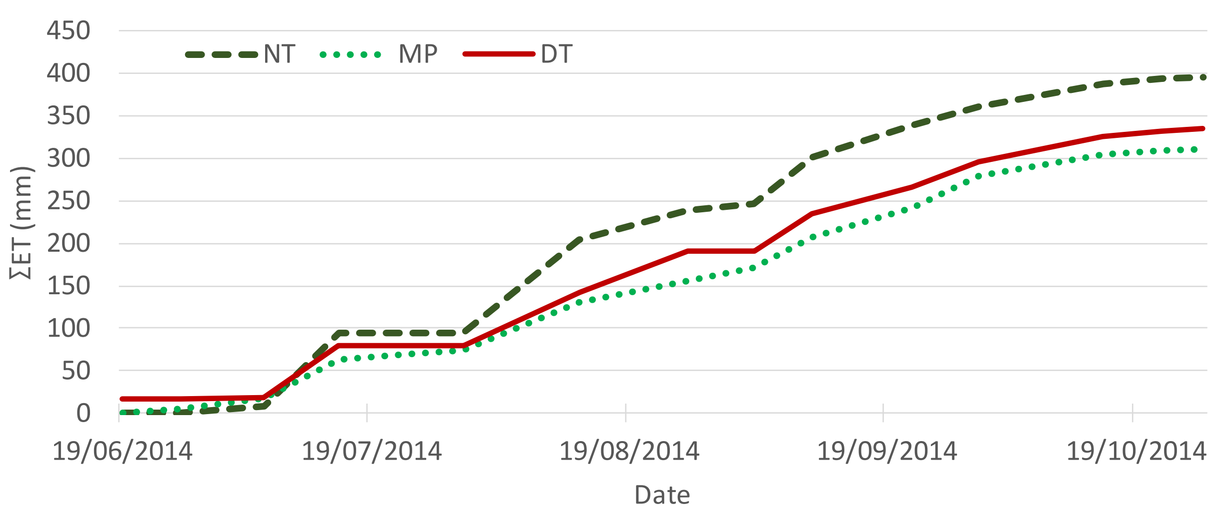


Figure 5.7: The effect of different tillage practices on cumulative ET of a McWMcW system throughout the 2014 growing season at Langgewens Research Farm

Canola after wheat in a WLWC system

The soil water balance calculated for canola after wheat in WLWC is summarized in *Figure 5.8.* Refer to Table 16, 17, 18 attached in Appendix B for detailed water balance sheets. During the period of 19 June to 13 August (20-74 days after planting) the cumulative ET (ΣET) values were the highest for the NT (125.1 mm) and DT (125.9 mm) treatments, whereas the ΣET for the MP treatment 88.6 mm. This observation was attributed to a higher SWC maintained by the DT and NT treatments at the beginning of the growing season. A visible increase in ΣET was seen from 13 August to 22 September (74-112 days after planting) for all treatments due to active crop growth during this period. Thereafter ΣET values gradually decreased till the end of the growing season. Although there was no significant difference found in ΣET values for all treatments at the end of the growing season the DT treatment (313.8 mm) resulted in the highest ΣET value, followed by the NT treatment (311.3 mm) and the MP treatment (283.8 mm) ($P = 0.1995$; CV = 10.21916). Drainage was extremely low for all treatments and in most cases = 0 for the same reasons as mentioned before.

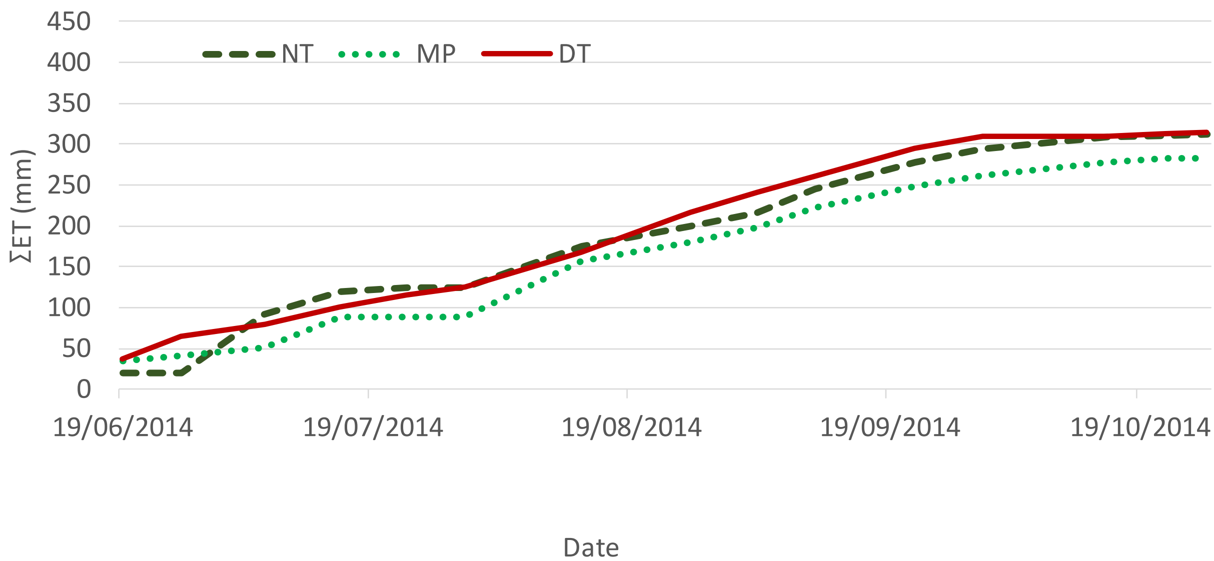


Figure 5.8: The effect of different tillage practices on ΣET of a WLWC system throughout the 2014 growing season at Langgewens Research Farm

Wheat after canola in LWCW

ET values calculated for wheat after canola in LWCW are summarized in *Figure 5.9*. Refer to *Appendix B* for detailed water balance sheets. Due to a low crop water demand ΣET values were low at the beginning of the growing season ranging between 0-78 mm for all treatments from 6 June to 30 July (7-60 days after planting). ΣET values were = 0 in cases where rainfall was constant, although in some cases in small amounts, and temperatures low. Therefore, circumstances did not allow for ET to take place. The highest ET values during this part of the season were observed for the MP and DT treatments. These observations are supported by the research of Jalota and Prihar, (1990) who similarly found higher ET amounts under CT practices. According to Jalota and Prihar tillage increases surface roughness which increases ET by concentrating heat in the surface layers and allowing greater wind penetration into the soil. Blevins et al., (1971) also came to the conclusion that NT systems result in lower ΣET during the early stages after plant due to residue cover which restricted evaporation. During the early stages of crop development foliar coverage does not play a role and therefore evaporation from the soil surface is the dominant component of soil water loss. After 30 July (60 days after planting) a dramatic increase in ΣET was observed for all treatments which can be explained by a high crop water demand due to active growth as well as an increase in SWC which took part from 16 to 30 July (46-60 days after planting). Precipitation values were also above average which also made a contribution towards the high ΣET values achieved. ΣET values ranged between 0-123 mm for all treatments from 13 August to 27 October (74-150 days after planting). Although not significantly different, the ΣET at the end of the season was the highest for MP (399.9 mm), followed by DT (386.8 mm) and NT (363.8 mm) at the end of the growing season ($P = 0.8572$; $CV = 24.74556$). The DT and MP treatments were more subjected to drainage (U) which may be explained by the loosening effect these tillage operations had on the soil leading to drainage of water downwards the profile out of reach of plant roots and therefore it had no effect on ΣET values.

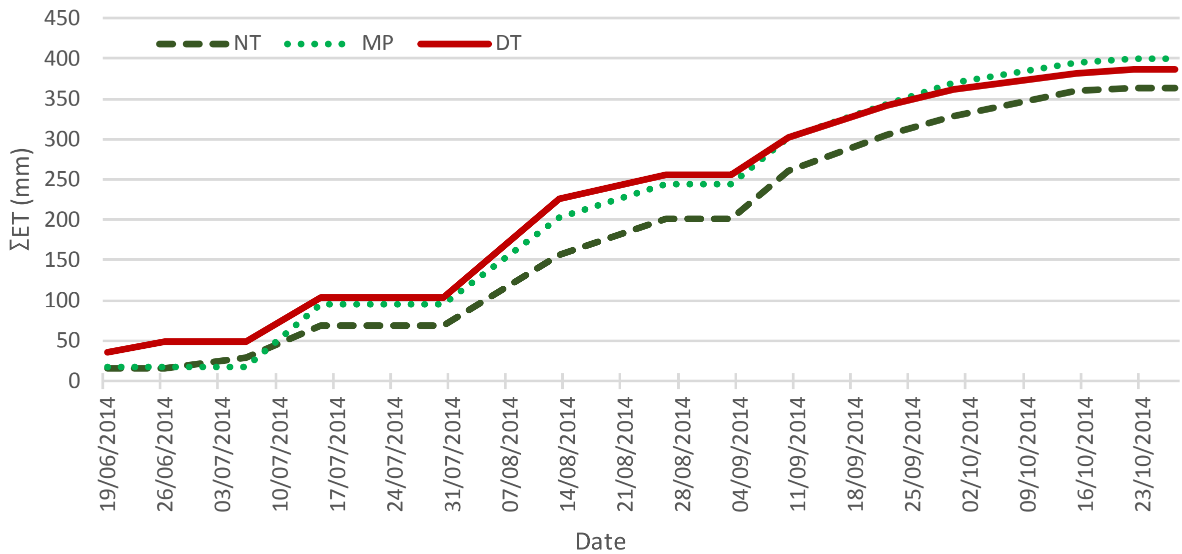


Figure 5.9: The effect of different tillage practices on ΣET of a LWCW system throughout the 2014 growing season at Langgewens Research Farm

5.2.2 Soil water balances for the 2014 fallow season

Refer to *Table 19-27* in *Appendix C* for statistics on monthly SWC measurements for the 2014/2015 fallow season.

5.2.2.1 Soil water content (SWC)

The SWC during the fallow period of November 2014-May 2015 was recorded at monthly intervals to a depth of 800 mm. Due to technical difficulties the SWC was not measured during the months of November and April. The soil water content was monitored during the fallow period in order to determine the capacity of the treatment combinations to store water between the growing seasons. Refer to *Figure 3.4* and *3.5* for rainfall data.

Wheat after medics in a McWMcW system

Both the NT and DT treatments underwent an approximately 50% decrease in SWC due to evaporation losses after harvest until 4 December while the MP treatment only lost 26% of its SWC as measured on 27 October (*Figure 5.10*). High evaporation losses were expected during the 38 days after harvest due to an average temperature of 27 °C and a total of 22.6 mm rainfall which was recorded before the next SWC measurement *(Figure 3.4 and 3.5).* The SWC for each tillage treatment did not vary much from 4 December to 11 May. The MP treatment stored 22% more water throughout the growing season compared to NT and 19% more water compared to the DT treatment. The water was mainly stored in the 400-800 mm soil depth. This observation may be attributed to a discontinuity effect caused by the MP tillage action at the depth of tillage. Several researchers reported that intensive CT systems destroy the discontinuity of macro-pores resulting in the reduction of upwards capillary movement of soil water under the influence of evaporation (Green et al. 2003; Osunbitan et al. 2005; Thierfelder, 2007). Therefore, the MP treatment stored a greater amount of water in the 400-800 mm soil depth compared to the DT and MP treatments throughout the fallow season (*Table 19, 20 and 21).* No significant difference in SWC was found for the McWMcW system between tillage treatments during the 2014/2015 fallow season (P = 0.05).

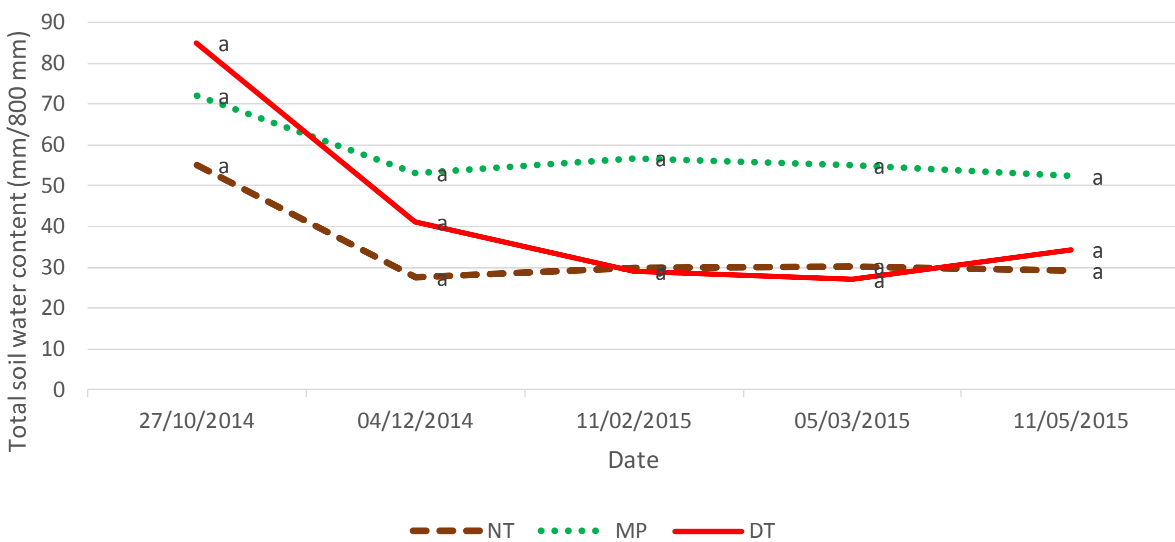


Figure 5.10: The effect of different tillage practices on the SWC of a McWMcW system throughout the 2014 fallow season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Canola after wheat in WLWC system

From 27 October to 4 December the NT treatment underwent a 32% decrease in SWC, the MP treatment a 13% decrease and the DT treatment a 41% decrease (Figure 5.11). As mentioned, high evaporation losses were expected during the 38 days after harvest due to an average temperature of 27°C and a total of 22.6 mm rainfall which was recorded before the next SWC measurement (*Figure 3.4 and 3.5*). The SWC for all treatments did not vary much from 4 December to 11 May. The NT treatment stored a total amount of 146 mm water during the fallow period, while the MP treatment stored a total amount of 144.5 mm and the DT treatment a total amount of 162.8 mm. No significant difference in SWC was found for the WLWC system between tillage treatments during the 2014/2015 fallow season (P = 0.05).

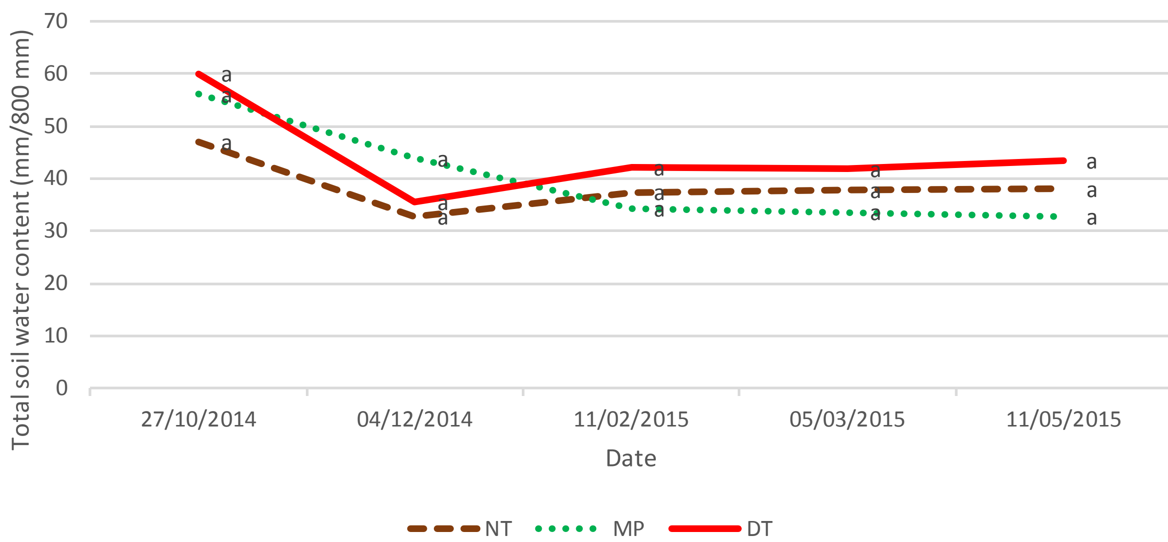


Figure 5.11: The effect of different tillage practices on the SWC of a WLWC system throughout the 2014 fallow season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Wheat after canola in LWCW system

The DT treatment stored the least amount of soil water from 27 October to 11 May. The DT treatment underwent the highest loss in SWC (58%), followed by the MP treatment (47%) and the NT treatment (41%) due to evaporation losses after harvest till 4 December (*Figure 5.12)*. High evaporation losses was expected during the 38 days after harvest due to an average temperature of 27°C and a total of 22.6 mm rainfall which was recorded before the next SWC measurement (*Figure 3.4 and 3.5*). According to thorough inspection of data all treatments 0-300 mm soil depth increment was measured at permanent wilting point, although 60% of the DT treatments measurements was measured at permanent wilting point during 27 October to 11 May. The low SWC under DT can be substantiated by Lipiec et al. (2006) who found that higher total porosities under DT results in higher evaporation and transpiration demands compared to NT. SWC for NT and MP treatments did not differ much throughout the growing season. The NT treatment stored 12% more water compared to the MP treatment and 17% more compared to the DT treatment throughout the fallow season. No significant difference in SWC was found for the LWCW system between tillage treatments during the 2014/2015 fallow season (P = 0.05).

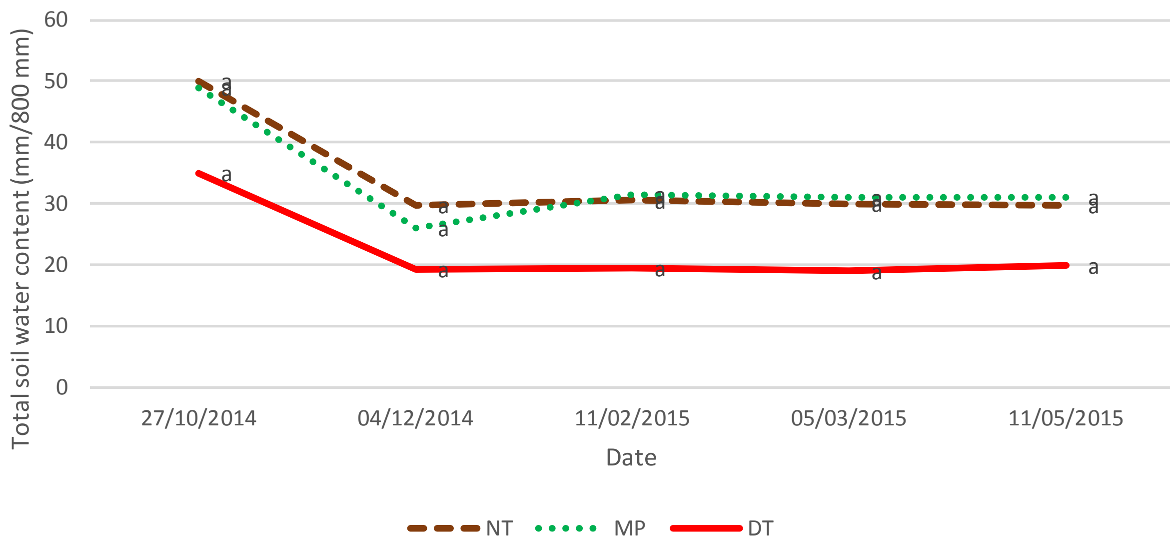


Figure 5.12: The effect of different tillage practices on the SWC of a LWCW system throughout the 2014 fallow season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

When comparing all three cropping systems according to their graphs it was clear that both the wheat after medic and canola after wheat systems maintained the highest SWC throughout the fallow season compared to the wheat after canola system. Values between 36.12-40.70 mm were recorded for the canola after wheat system, while values between 29.20-54.28 mm were recorded for the wheat after medic system. The wheat after canola system maintained water content values between 19.43-30.03 mm throughout the fallow season.

5.2.2.2 Cumulative evaporation (ΣE) and drainage/deep percolation (U)

ΣE and U were calculated for each treatment combination from water balances attached (*Appendix C*). The water balance was determined by monitoring monthly soil water contents and rainfall events. Thereafter Hillel's (1998) equation *(Equation 2)* was used to determine the soil water balance from which the ΣE and U was determined. Both the ΣE and U was determined with *Equation 3*. Refer to *Chapter 3 Section 2.7.3.1.3* for a detailed explanation of the equation. Due to technical difficulties the ΣE and U was not determined for November and April 2014.

ΣE values gradually increased due to a gradual increase in temperature and scarce rainfall throughout the 2014/2015 fallow season. For the LWCW system the highest ΣE values were obtained for the NT treatment while the lowest ΣE values were obtained for the DT treatment throughout the fallow season. The higher ΣE under NT can be explained by Moret et al. (2007) who attributed the higher evaporation under NT to higher topsoil water contents which enhanced soil water evaporation. In *Table 24, 23 and 22* (*Appendix C*) it was clear that the NT treatment maintained a higher SWC throughout the growing season and therefore it was subjected to more evaporation. In the WLWC system the MP treatment maintained the highest ΣE throughout the fallow season. ΣE values for both the DT and NT treatments did not variate much. For the McWMcW system the highest ΣE values were obtained for the MP and DT treatments while the lowest ΣE value was obtained for the NT treatment. These results can again be substantiated by Jalota et al. (2006) who similarly observed lower evaporation values under NT due to the accumulation of surface coverage.

5.2.3 Soil water balances for the 2015 growing season

5.2.3.1 Soil water content (SWC)

Refer to Table 28-36 in *Appendix D* for statistics on weekly SWC measurements for the 2015 growing season. Refer to *Figure 3.5* for rainfall data.

Medic after wheat in WMcWMc system

The influence of once-off tillage on the soil water content (mm/800 mm) of canola after wheat in the WMcWMc system during the 2015 growing season is summarized in *Figure 5.13.* SWC readings remained between 27-129 mm for the whole growing season. A low amount of water was carried over from the fallow season to the 2015 growing season due to evaporative losses under the influence of high temperatures, low rainfall and low surface coverage and therefore SWC readings were low at the beginning of the growing season. No clear trend in SWC was observed at the beginning of the growing season and SWC readings varied according to rainfall events and temperature. As for the same reasons as mentioned for the WLWC system, a decrease in SWC was observed between 3 to 13 July (14 days after planting-24 days after planting) where after an increase in SWC was observed until the end of July due to big rainfall events (43.6 mm). The highest rainfall amount (32.2 mm) was recorded during 23 to 31 July which resulted in greater increases in SWC for MP and DT compared to NT. A significant higher SWC was recorded for MP compared to DT and NT on 27 August (99 days after planting; $P = 0.0146$) and 3 September (106 days after planting; $P = 0.0135$), while on 23 September (126 days after planting) a significant difference was found between MP and DT treatments ($P = 0.0153$). There was no significant difference in SWC between all treatments on all other measured dates (P = 0.05). A gradual decrease in SWC was recorded from 14 August to 27 October (86-163 days after planting) for all tillage treatments tested which was attributed to a high evapotranspiration demand of crops reaching maturity and low rainfall.

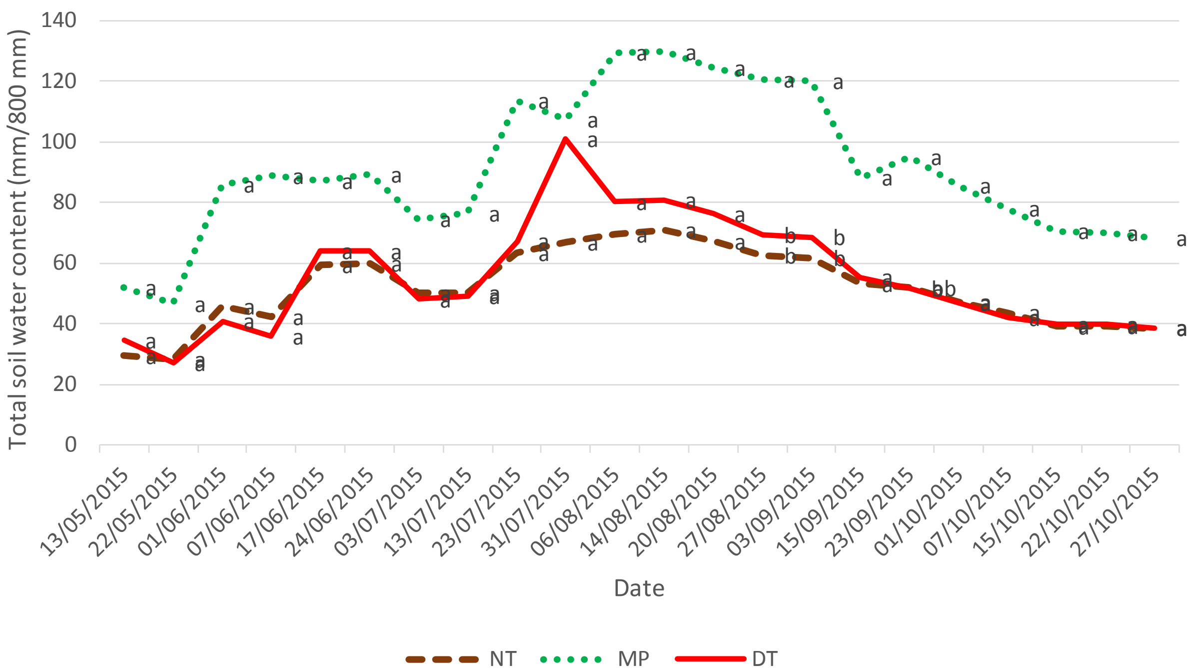


Figure 5.13: The change in SWC of a WMcWMc system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Wheat after lupine in a CWLW system

The influence of once-off tillage on the soil water content (mm/800 mm) of canola after wheat in the CWLW system during the 2015 growing season is summarized in *Figure 5.14*. SWC readings remained between 18-120 mm for the whole growing season. A low amount of water was carried over from the fallow season to the 2015 growing season and therefore SWC readings were low at the beginning of the season due to the same reason as mentioned earlier Initially SWC readings were low from 13 May (7 days before planting) to 7 June (18 days after planting) due to high average temperatures and low rainfall (18.9°C, 1.86 mm). As for the same reasons as mentioned for the WLWC system, a decrease in SWC was observed between 24 June to 13 July. A gradual decrease in SWC was recorded between 31 July and 27 October (72-159 day after planting) for all tillage treatments tested which was attributed to high evapotranspiration demand of crops reaching maturity and low rainfall. With exception of 22 May (2 days after planting) and 1 June (12 days after planting) the MP treatment maintained the highest SWC throughout the growing season, while with exception of 17 June the NT treatment maintained the lowest SWC throughout the growing season. A significantly higher SWC was observed for the MP treatment compared to the NT and DT treatment on 24 June (P = 0.0542), 3 July (P = 0.0457), 13 July (P = 0.0651) and 23 July (P = 0.0719), while on all other measured dates no significant difference in SWC was found between treatments (P = 0.05).

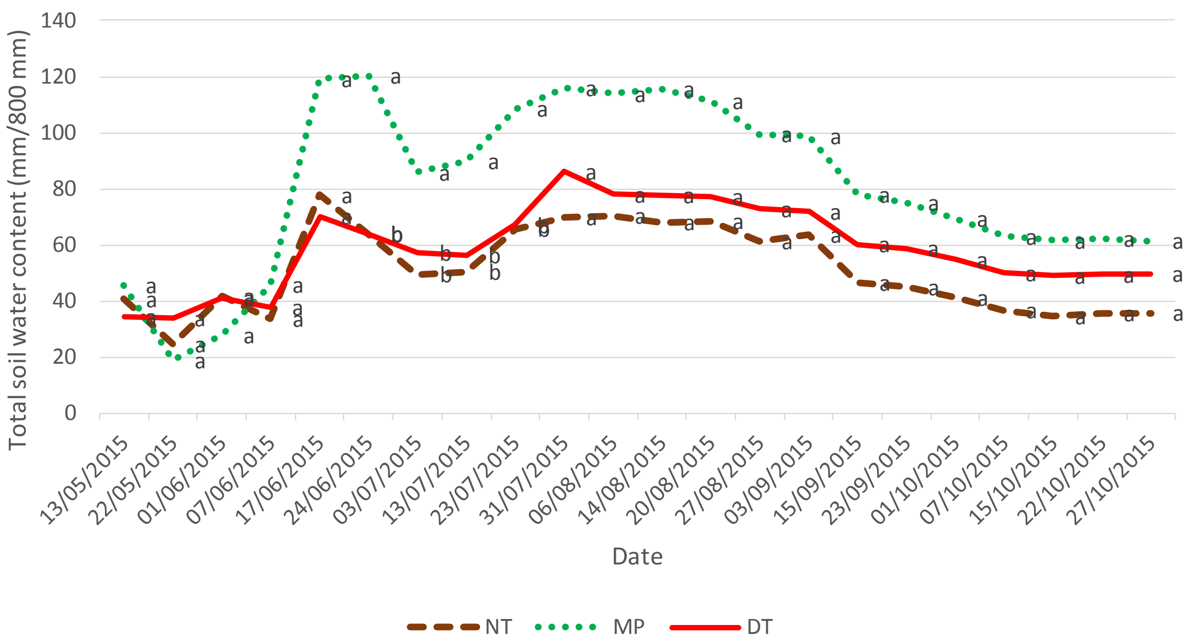


Figure 5.14: The change in SWC of a CWLW system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Canola after wheat in a WLWC system

The influence of once-off tillage on the soil water content (mm/800 mm) of canola after wheat in the WLWC system during the 2015 growing season is summarized in *Figure 5.15*. A low amount of water was carried over from the fallow season to the 2015 growing season and therefore SWC readings were low at the beginning of the season due to the same reason as mentioned before. With the exception of 13 May (DT) and 22 May (DT and MP) the SWC remained between 20-75 mm for the whole growing season. On 22 May a significantly higher SWC was observed for the NT treatment compared to the DT treatment (P = 0.0705). Soil water content varied according to rainfall, temperature and evapotranspiration demands.

The average temperature of 17.5°C and rainfall of 2.8 mm between 1 to 17 June (12-29 days after planting), 20°C and 1.02 mm rainfall between 13 May to 1 June (7 days before planting to 12 days after planting) and 17.3°C and 0.65 mm rainfall recorded between 24 June to 13 July (35-54 days after planting) resulted in sharp SWC decreases for all tillage treatments. A gradual decrease in SWC was recorded between 6 August and 27 October (78-159 day after planting) for all tillage treatments tested which was attributed to high evapotranspiration demand of crops reaching maturity and low rainfall. With exception of 31 July (72 days after planting) the highest SWC readings were measured for the MP treatment between 13 July and 27 October (24-159 days after planting). No definite trend in SWC was observed for the DT and NT treatments. With exception of 22 May no significant difference in SWC was found between all tillage treatments at all measured dates (P = 0.05).

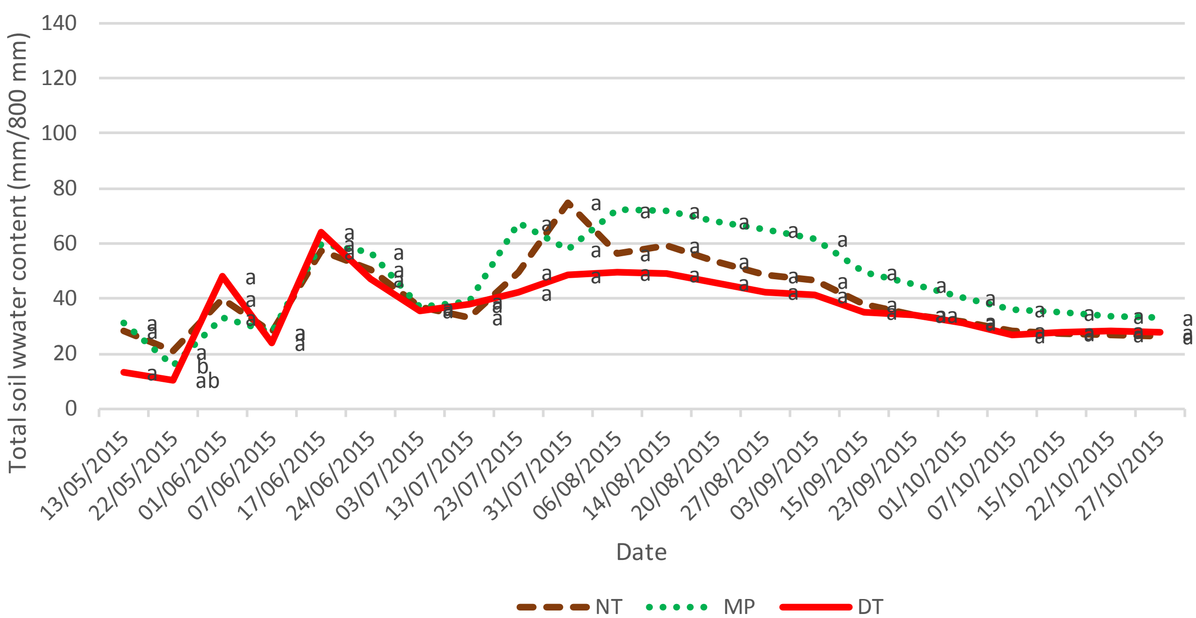


Figure 5.15: The change in SWC of a WLWC system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

When comparing all three cropping systems according to their graphs no clear similarity was observed. Both the medic after wheat and wheat after lupin systems maintained the highest water content throughout the growing season compared to the canola after wheat system. Values between 27-129 mm for the medic after wheat system was achieved, while values between 18-120 mm was achieved for the wheat after lupins system. The canola after wheat system maintained water content values between 10-75 mm throughout the growing season. Both the wheat after lupin and the medic after wheat systems showed sharp increases in soil water content after rainfall events, while the canola after wheat showed much lower increases. For all three cropping systems the MP treatment tended to maintain the highest SWC throughout most part of the growing season. The 0-400 mm and 400-800 mm soil depths were thoroughly investigated to find an explanation for the high SWC for the MP treatments.

After thorough inspection of the whole profile SWC it was found that rainwater infiltrated the 0-400 mm soil depth increments (the layer on top of the shale layer) after rainfall events, but what was however found was that water suddenly started to increase in greater amounts from the 800 mm soil depth upwards in the profile in about 5 days after a rainfall event occurred. All sites were situated against a slope as can be seen in *Figure 3.2 and Figure 3.3*. The sites at the top of the slope were under fallow management and are situated next to great road reserves which are subjected to the infiltration of great amounts of water after rainfall events. Water that infiltrated the fallow sites and roads may have infiltrated down the profile towards the shale layer which is vertically oriented and therefore allowed the lateral movement of water down the slope through the vertical oriented shale layers.

5.2.3.2 Soil water content for the 0-400 mm and 400-800 mm depth increments

The soil water content was determined for the 0-400 mm and the 400-800 mm soil depths in order to determine which soil depth increment stores the most amount of water. It was expected that the 400-800 mm soil depth (the shale layer) would store the largest amount of water. During the 2015 growing season the MP treatment stored the most water compared to the other tillage treatments. It was however observed that the MP treatment stored the most amount of water in the 400-800 mm soil depth. It was suspected that the reason for the high SWC in the 400-800 mm soil depth was attributed to the inefficient use of the available water by the crops present. Therefore, the MP treatments 0-400 mm and 400-800 mm soil depths were thoroughly investigated in order to draw a conclusion regarding whether the crop roots reached the 400-800 mm soil depth. Refer to *Appendix D*, *Table 28-36* for detailed soil water balance sheets and statistics on the 0-400 mm and 400-800 mm depth increments. Refer to *Appendix A, Table 1-9* for detailed soil classification and profile descriptions.

Medic after wheat in a WMcWMc system

SWC was low at the beginning of the growing season (13 May-22 May) ranging between 19.6-31.8 mm for all tillage treatments in the 400-800 mm soil depth and between 7.5-14.6 mm for all tillage treatments in the 0-400 mm soil depth (*Figure 5.16*). After 20 May an increase in SWC was observed for all treatments in the 0-400 mm soil depth, while only the MP treatment did not show a decrease in SWC in the 400-800 mm depth after the latter mentioned date. However, a decrease in SWC was observed for the MP treatment (400-800 mm) after 7 June while all the other treatments showed an increase in SWC. This phenomenon may be attributed to the MP treatments high SWC in the 400-800 mm soil depth making it less sensitive to SWC decreases/increases under the influence of temperature, evaporation and transpiration. No clear trend in SWC was observed between 17 June and 13 July as all treatments reacted differently towards rainfall or temperature increases or decreases. From 13 July to 23 July an increase in SWC occurred for all treatments in both the 0-400 mm and 400-800 mm soil depth due to high rainfall events and low temperatures recorded. Between 23 July and 31 August increases in SWC were only observed for DT (400-800 mm and 0-400 mm) as well as for NT (400-800 mm) while decreases were observed for all the other treatments. From 14 August SWC gradually decreased/increased according to rainfall, temperature and crop water uptake. The clear decrease in SWC observed from 3-15 September was attributed to an average temperature of 22.5°C. In both the 0-400 mm and 400-800 mm soil depth the MP treatment maintained the highest SWC throughout the growing season while the lowest total amount of stored soil water was recorded for the NT treatment. In the 0-400 mm soil depth a total amount of 1522.58 mm was stored throughout the growing season while in the 400-800 mm soil depth a total amount of 2825.98 mm soil water was stored in the 400-800 mm depth. For the MP treatment no significant difference in SWC was observed on 24 June between the 0-400 mm and 400-800 mm soil depths ($P = 0.05$), while a significant difference between the depth increments were observed for all other measured dates ($P < 0.0001$). From 17 June-23 July no significant difference was observed in SWC between the DT (0-400 mm) and DT (400-800 mm) treatments ($P = 0.05$), while for all other measured dates significant differences were observed ($P < 0.0001$). From 1 June-23 July no significant difference was observed between the 0-400 mm (NT) and the 400-800 mm (NT) treatments ($P = 0.05$), while on all other measured dates significant differences were observed ($P < 0.0001$).

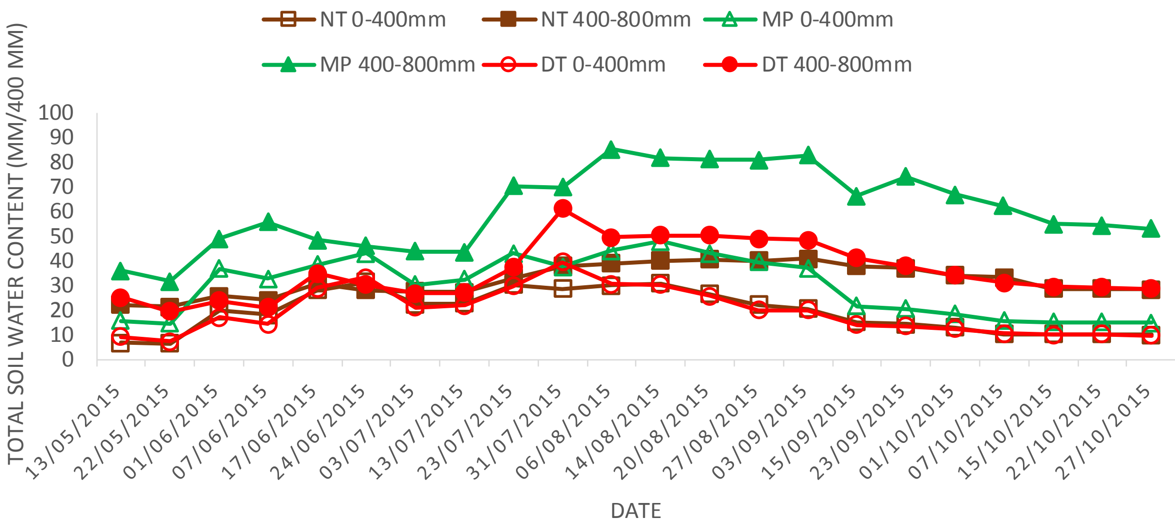


Figure 5.16: The change in SWC between tillage treatments for the 0-400 mm and 400-800 mm depth increments of a WMcWMc system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Wheat after lupine in a CWLW system

SWC was low at the beginning of the growing season (13 May-1 June) ranging between 10.0-38.5 mm for all tillage treatments in the 400-800 mm soil depth and between 3.6-12.6 mm for all tillage treatments in the 0-400 mm soil depth (*Figure 5.17*). The low water content values measured in the 0-400 mm soil depth caused the SWC to be at the lowest boundary of plant available water for 73% (NT), 33% (MP) and 82% (DT) of the total growing season time. From 1 June to 17 June a steep increase in SWC was observed for all treatments with a 33.5-71.0 mm increase in SWC for all treatments in the 400-800 mm soil depth and a 3.9-9.0 mm increase in the 400-800 mm soil depth. Decreases in SWC were observed for all treatments in both depth increments between 26 June and 3 July where after SWC gradually increased till 24 July. The decrease in SWC can be explained by low rainfall combined with active uptake of water by crops during 26 June to 3 July (37-45 days after planting). From 24 to 31 July all treatments showed increases in SWC while the NT treatment (400-800 mm) showed a decrease in SWC. A total amount of 32.2 mm rainfall was recorded during the latter mentioned time period and therefore the fact that no increase in SWC occurred for the NT treatment (400-800 mm) may be explained to the fact that the rain water did not drain downwards to the 400-800 mm soil depth after the rainfall event occurred. After thorough inspection of the soil water balance sheet for the CWLW NT treatment it was indeed confirmed that no downwards drainage occurred for NT (400-800 mm) possibly due to crop roots actively taking up water in the 0-400 mm soil depth. From 14 August (86 days after planting) the SWC for all treatments started to gradually decrease. The higher temperatures and lower rainfall amounts recorded after 14 August contributed to the decrease in SWC. With exception of the MP treatment between 29 May and 1 June all treatments in the 400-800 mm soil depth maintained a higher SWC compared to all the treatments in the 0-400 mm soil depth. In both the 0-400 mm and 400-800 mm soil depth the MP treatment stored the highest amount of water throughout the growing season while the DT treatment stored the lowest amount of water in both the 0-400 mm and 400-800 mm soil depth. The 400-800 mm soil depth increment stored a total of 3268.45 mm water while the 0-400 mm soil depth stored a total amount of 934.82 mm throughout the 2015 growing season. For both the NT and DT treatments significant differences in SWC between the 0-400 mm and 400-800 mm soil depths were observed on all measured dates ($P < 0.0001$). For the MP treatment no significant difference in SWC was observed on 1 June ($P = 0.0385$), while significant differences were observed on all other measured dates between the 0-400 mm and 400-800 mm soil depths ($P < 0.0001$).

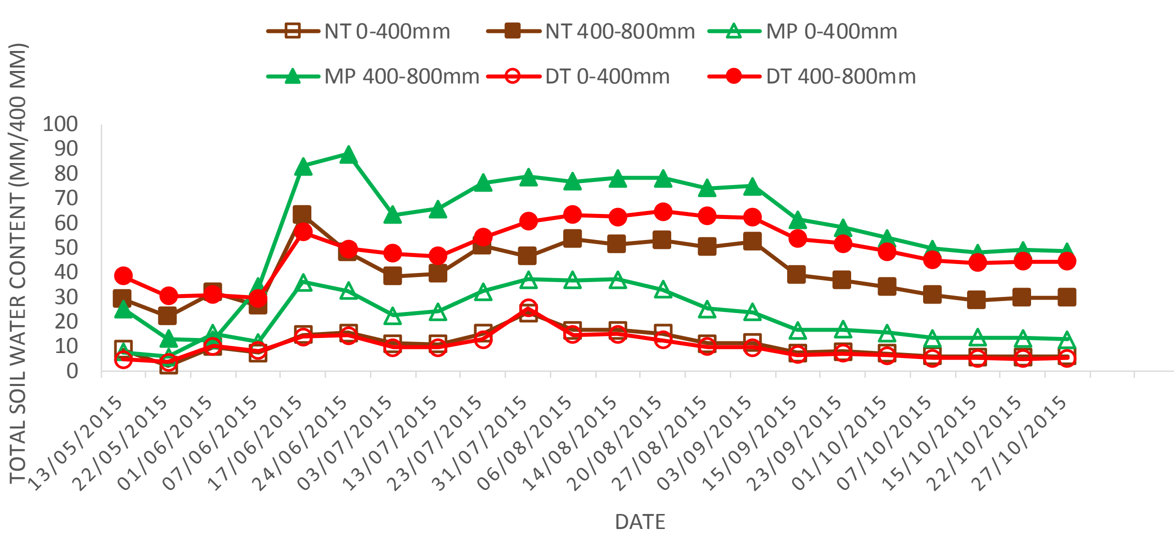


Figure 5.17: The change in SWC between tillage treatments for the 0-400 mm and 400-800 mm depth increments of a CWLW system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Canola after wheat in a WLWC system

According to *Figure 5.18* the lowest SWC was obtained in the 0-400 mm depth during the whole growing season. The low SWC readings caused the SWC to be at the lowest boundary of plant available water for 65% (NT), 72% (MP) and 98% (DT) of the total growing season time. From 13 May to 17 June the SWC for all treatments in both the 0-400 mm and 400-800 mm soil depth reacted accordingly to temperature increases/decreases and rainfall events. In the 400-800 mm soil depth the DT treatment showed the highest increase in SWC compared to both the MP and DT treatments after rainfall events which took place before 1 June and 17 June. After thorough inspection of the water balance data it was clearly observed that 88% less water was stored on 1 June and 89% less water on 17 June in the 0-400 mm soil depth compared to the 400-800 mm depth and therefore the higher increase in SWC under DT in the 400-800 mm soil depth may be contributed to the presence of preferred channels in the 0-400 mm depth to the 400-800 mm depth which was created by the deep tine tillage action. From 17 June to 24 June all treatments in the 400-800 mm depth showed a decrease in SWC while all treatments in the 0-400 mm depth showed an increase in SWC. From 23 July to 6 August the NT (0-400 mm and 400-800 mm) and the DT (0-400 mm) showed an increase in SWC while all other treatments in both depths showed SWC decreases. From 14 August till the end of the growing season gradual decreases in SWC was observed for all tillage treatments in both the 0-400 and 400-800 mm depths. In the 400-800 mm soil depth the MP treatment stored the highest total amount of water throughout the growing season while the NT treatment stored the lowest amount of water. In the 0-400 mm soil depth the NT treatment stored the highest amount of water while the DT treatment stored the lowest amount of water. The 0-400 mm soil depth stored a total amount of 664.5 mm while the 400-800 mm soil depth stored a total amount of 2087.02 mm throughout the growing season. For both the DT and MP treatments significant differences in SWC were found between the 0-400 mm and 400-800 mm soil depths ($P < 0.0001$). For NT no significant difference was found in SWC on 13 July between the 0-400 mm and 400-800 mm depth increments ($P = 0.0050$) while a significant difference were found between the increments on all other measured dates ($P < 0.0001$).

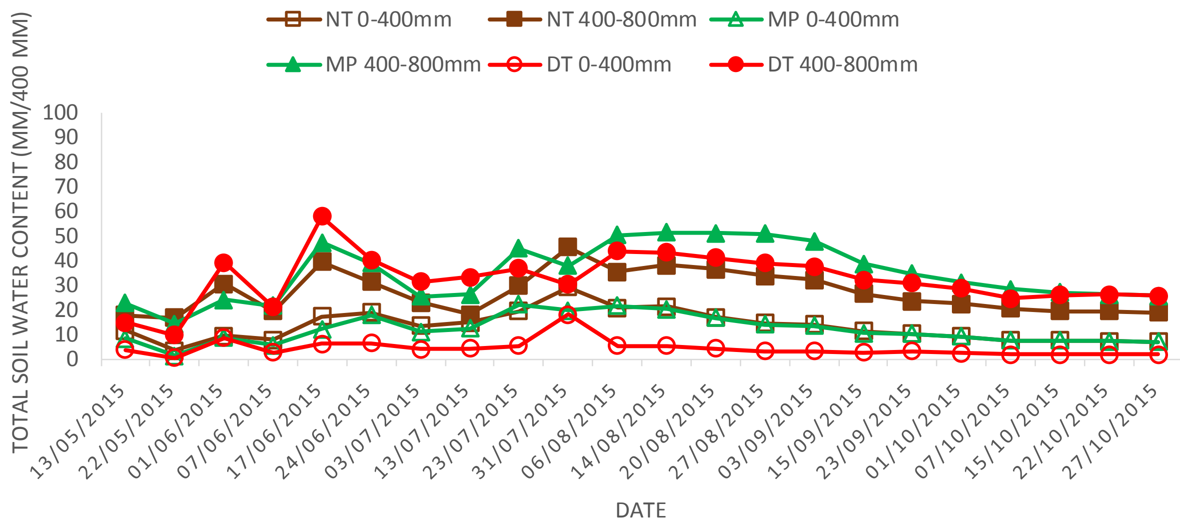


Figure 5.18: The change in SWC between tillage treatments for the 0-400 mm and 400-800 mm depth increments of a WLWC system throughout the 2015 growing season at Langgewens Research Farm

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Generally, significantly higher SWC readings were observed in the 400-800 mm soil depth compared to the 0-400 mm soil depth ($P < 0.0001$) for all tillage treatments and crop rotation systems throughout the 2015 growing season. Thorough inspection of soil water balance sheets clearly showed decreases in SWC in the 0-400 mm soil depth and increases in SWC in the 400-800 mm soil depth after rainfall events. The lateral movement of soil water in the shale layer from nearby fallow lands and road reserves may also have contributed to the higher SWC in the 400-800 mm soil depth.

Several factors may have contributed to the higher SWC under MP. A well-developed structure consisting of a continuous macro-pore system as well as channels resulting from biological activity developed during the 7 year NT system (Blackwell et al., 1990; Wiermann et al., 2000; Schaffer et al., 2006). The once-off tillage action via MP or DT was conducted during very dry soil conditions on a soil that contains a fairly high clay content (average 15%) and therefore it may be possible that the volume of macro-pores increased through the tillage action which took place to a depth of 300 mm for MP and 400 mm for DT. Due to prevailing dry conditions in 2015 particle resettlement may not have taken place to such an extent to result in porosity decreases.

Higher SWC readings were observed for DT compared to NT in the 400-800 mm soil depth. The latter phenomenon may be explained by the DT implements tine spacing (200 mm) which may have caused less disturbance of the macro-pore system compared to MP and therefore higher porosities may have resulted under DT compared to NT which led to higher infiltration rates. The results obtained do not however correlate with results found by Schaffer et al. (2006) who found that tillage after a NT system leads to the disruption of the soils macro-pore system which results in infiltration decreases. Soil properties greatly differed for Schaffer et al. (2006) compared to soil properties at Langgewens and therefore similar results were not expected. Generally, the lowest infiltration rates were observed for MP, but due to the higher soil water contents observed in the 0-400 mm soil depth for MP compared to DT and NT it was concluded that water did efficiently infiltrate the surface of MP plots.

Another explanation for the higher SWC under MP may be ascribed to the inefficient uptake of water by crop roots. SWC readings in the 0-400 mm depth for DT and NT were near the lowest boundary of plant available water for most part of the growing season. The latter observation was not found to such a big extent for MP as much less SWC readings near the lowest boundary of plant available water were found for MP. The nearest boundary for plant available water was determined by Swiegelaar (2013) as part of a study conducted at Langgewens. Similar to Swiegelaar (2013) the nearest boundary for plant available water was found to be 3.6 mm/100 mm, while field capacity was measured at a value of 26 mm/100 mm. According to Swiegelaar (2013) active root growth is greatly disabled at a water content lower than 3.6 mm/100 mm. Therefore, there was claimed that the roots must have obtained most of their water from the 400-800 mm soil depth otherwise crops would have died off. A similar conclusion was obtained by Swiegelaar (2013) who also conducted research at Langgewens. Vorster (2015) also concluded that roots obtain most of their water from the 400-1000 mm soil depth if SWC readings are too low for active root growth in the 0-400 mm soil depth.

A definite conclusion regarding the higher SWC under MP could not be made due to limited research on the soil water balance topic.

5.2.3.3 Cumulative ET (ΣET) and drainage/deep percolation (U)

Refer to *Appendix D*, *Table 28-36* for the 2015 growing season soil water balance sheets.

Medic after wheat in a WMcWMc treatment

The soil water balance calculated for medic after wheat in WMcWMc is summarized in *Figure 5.19.* Due to a low crop water demand ΣET values were low at the beginning of the growing season ranging between 11.9-18.0 mm for all treatments from 22 May to 7 June (2-18 days after planting) where after ΣET values gradually increased for all tillage treatments until 15 October (128 days after planting). From 15 October till the end of the growing season (155-167 days after planting) ΣET values remained constant until the end of the growing season for all tillage treatments. The gradual increase in ΣET values can be explained by an increasing crop water demand as explained before for other systems. The constant ΣET values obtained during 17 to 27 October (132-142 days after planting) can be explained by a lower crop water demand. With exception of 22 July to 2 August the lowest ΣET values were observed for the NT treatment. No clear trend was observed for both the MP and DT treatments. ΣET values remained between 11.9-167.7 mm for NT, 16.0-207.2 mm for MP and 18.0-197.2 mm for DT. At the end of the 2015 growing season a significantly higher ΣET value was found for the MP treatment compared to the NT treatment, while no significant difference was found between DT and MP nor DT and NT ($P = 0.2611$). The significantly higher ΣET observed for the MP treatment may be attributed to a higher evaporation demand due to a higher SWC compared with more surface exposure compared to other treatments during the dry growing season. Similar results were obtained by Moret et al (2007) under similar conditions, but not similar tillage treatments. The transportation of the medic seeds through the turnover effect of the mouldpoard plough to deeper soil layers resulted in seedling emergence delays as well as unsuccessful seedling emergence in some cases. Therefore, due to lower crop densities, more soil surface exposure, the medic plots were subjected to a higher evaporation demand and a lower transpiration demand.

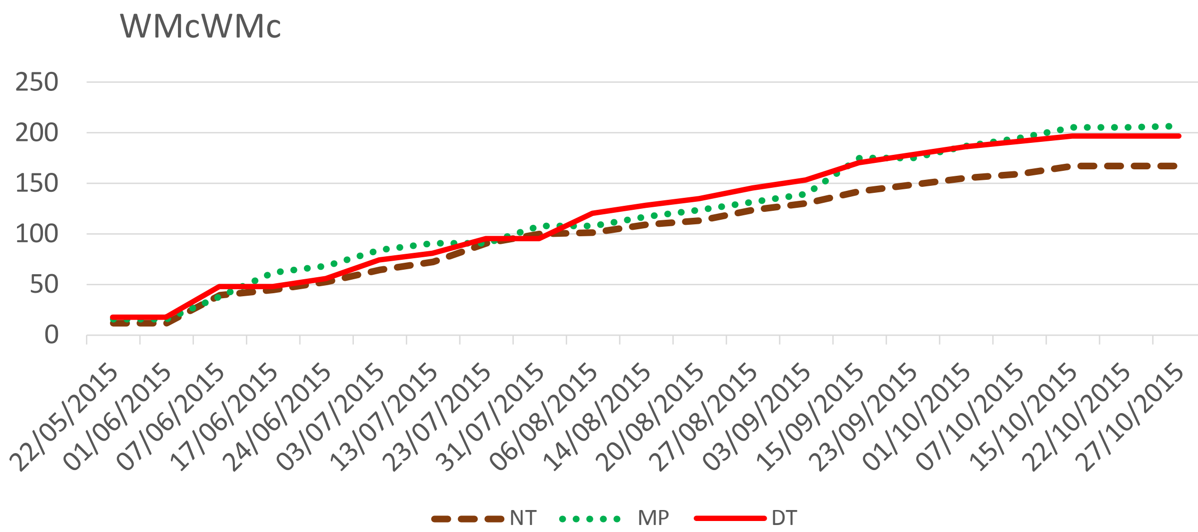


Figure 5.19: The effect of different tillage practices on cumulative ET of a WMcWMc system throughout the 2015 growing season at Langgewens Research Farm

Wheat after lupine in a CWLW system

The soil water balance calculated for wheat after lupine in CWLW is summarized in *Figure 5.20.* Due to a low crop water demand ΣET values were low at the beginning of the growing season ranging between 19.9-56.5 mm for all treatments from 22 May to 20 June (2-31 days after planting). After 20 June (31 days after planting) ΣET values gradually increased for all tillage treatments until 17 October (130 days after planting) where after ΣET values remained constant until the end of the growing season for all tillage treatments. The gradual increase in ΣET values can be explained by an increasing crop water demand due to active growth as well as an increase in SWC which took part from 7 to 17 June (18-28 days after planting). The constant ΣET values obtained during 17 to 27 October (132-142 days after planting) can be explained by a lower crop water demand due to crops reaching maturity. From the beginning till the end of the growing season ΣET values remained the highest for the NT treatment ranging between 23.8-201.5 mm. This result correlates with research conducted by Moret et al., (2007) who similarly found higher ΣET values under a NT system compared to a CT system. They attributed the higher ET under NT to higher topsoil water contents which enhanced soil water evaporation. For the 2015 growing season ΣET values for the MP treatment ranged between 24.6-192.3 mm while ΣET values for DT ranged between 19.9-181.1 mm. Lower ΣET values was observed for the MP treatment from the beginning of the growing season to 3 July (44 days after planting) which may be attributed to a delay in germination and a longer time period of seedling establishment. Another decrease in ΣET values for MP was observed from 13 July to 3 August

(54-74 days after planting) where after higher ΣET values was observed for the DT treatment compared to MP. The MP treatment showed the highest SWC from 17 June (28 days after planting) till the end of the growing season but in contrast the lowest ΣET which was attributed to an inefficient use of available soil water possibly due to poor crop establishment. Although lower ΣET values was observed for DT, the DT treatment showed a very similar trend in ΣET increases/decreases. The highest drainage amounts occurred under the MP system (51.8 mm), followed by the NT treatment (30.3 mm) and lastly the DT treatment (18.5 mm). This result may be explained by the fact that inwards free flow/deep percolation of water from the plots next to the plots under observation occurred. No significant difference in ΣET was found between all treatments at the end of the 2015 growing season (P = 0.0768).

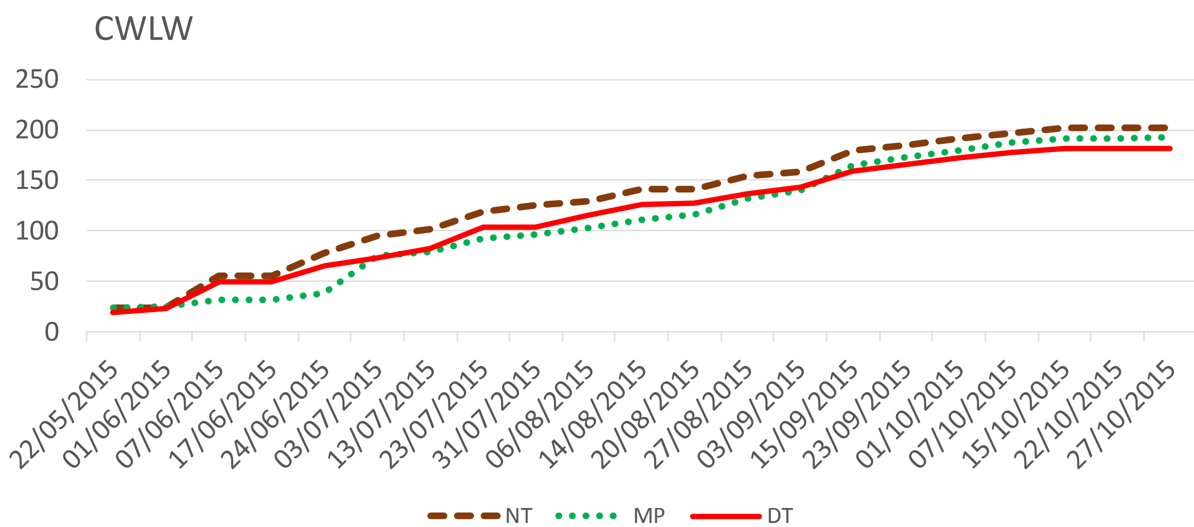


Figure 5.20: The effect of different tillage practices on cumulative ET of a CWLW system throughout the 2015 growing season at Langgewens Research Farm

Canola after wheat in WLWC system

ET values calculated for canola after wheat in WLWC is summarized in *Figure 5.21.* Due to a low crop water demand ΣET values were low at the beginning of the growing season ranging between 19-67 mm for all treatments from 22 May till 20 June (2-31 days after planting). After 20 June (31 days after planting) ΣET values started to gradually increase for all tillage treatments till 7 October (140 days after planting) where after ΣET values remained constant till the end of the growing season for all tillage treatments. The gradual increase in ΣET values can be explained by a high crop water demand due to active growth as well as an increase in SWC which took part from 7 to 17 June (18-28 days after planting). The constant ΣET values obtained during 10 to 27 October (132-142 days after planting) can be explained by a lower crop water demand due to crops reaching maturity. From 22 May to 1 July the lowest ΣET values were obtained for the DT treatment (2-12 days after planting) but there after ΣET values for the DT treatment remained the highest till the end of the growing season. Similar results were found by Jalota and Prihar, (1990) who similarly found higher ΣET amounts under CT practices. According to Jalota and Prihar (1990) tillage increases surface roughness which increases ΣET by concentrating heat in the surface layers and allowing greater wind penetration into the soil. ΣET values ranged between 26-194 mm for MP and 19.5-203.1 mm for NT throughout the 2015 growing season. From 6 August to 27 October (77-167 days after plating) the lowest ΣET values was observed for the MP treatment. The MP treatment contained the highest SWC during the latter mentioned part of the growing season and therefore it was concluded that there may have been an inefficient use of the available water by the crops present. No significant difference in ΣET was found between all treatments at the end of the 2015 growing season (P = 0.08147). ΣET values were however the highest for DT (206.3 mm), followed by NT (203.1 mm) and MP (194.6 mm). All treatments were subjected to drainage (U) which may be explained by the drainage of water downwards the profile out of reach of plant roots and therefore it had no effect on ΣET values.

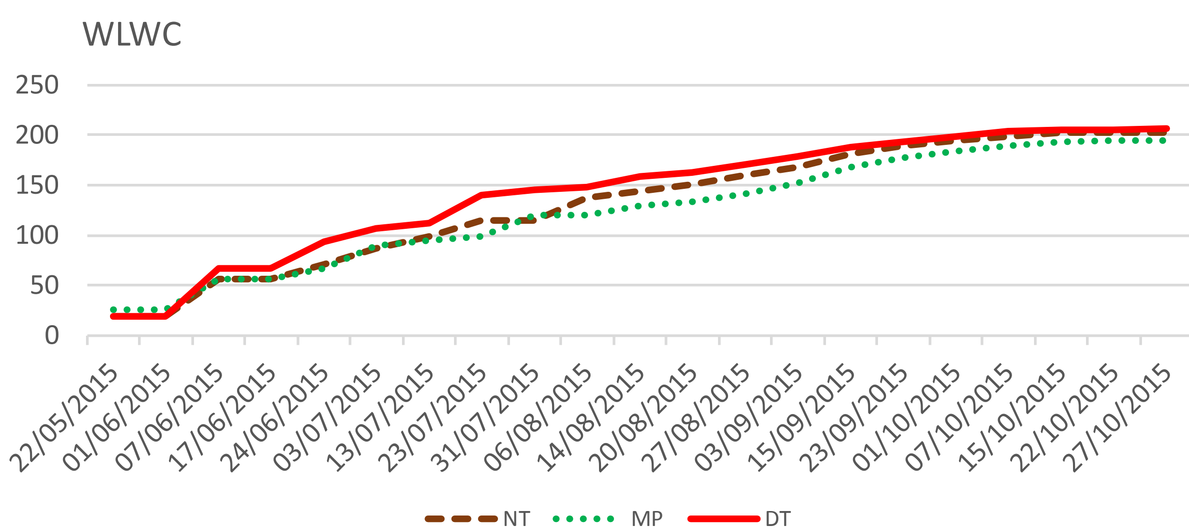


Figure 5.21: The effect of different tillage practices on cumulative ET of a WLWC system throughout the 2015 growing season at Langgewens Research Farm

5.3 Conclusion

Tillage had no consistent effect on SWC as significant differences in SWC was only observed on 30 July, 22 and 27 October for the wheat after canola system during the 2014 growing season. Significant differences were observed between NT and DT after big rainfall events and at the end of the growing season. SWC readings in 2014 ranged between 35-270 mm for all tillage treatments and crop rotation systems measured. No conclusion regarding the tillage treatment capable of storing the highest amount of water could be made as different trends were observed for different treatments and crop rotation systems. ET values varied according to the crop's development stage as well as the available SWC and external environmental factors (rainfall and temperature). Tillage had no significant effect on ET as no significant difference in ΣET was observed at the end of the 2014 growing season. No trend regarding the tillage treatment capable of storing the most amount of water was observed during the 2014/2015 fallow season as different treatments resulted in a higher SWC for each crop rotation system. More valuable results would have been obtained during the fallow season if technical difficulties could have been overcome. The total amount of rainfall recorded during the 2015 growing season was 31% lower compared to rainfall recorded during 2014 and therefore SWC readings during the 2015 growing season ranged between 10-140 mm which is much lower compared to the 36-269 mm recorded during 2014. In 2015 MP tended to result in the highest SWC for all crop rotation systems and on several dates significantly higher SWC readings were observed for MP compared to NT and DT. Due to scarcity of research on the soil water balance topic a definite conclusion regarding the higher SWC under MP could not be drawn. MP resulted in a significantly higher ΣET at the end of the 2015 growing season for the WMcWMc system. The latter result was attributed to a higher evaporation demand during the dry 2015 growing season due to higher soil water contents, lower crop densities as well as lower crop stands.

Chapter 6: The effect of once-off tillage on the water use efficiency (WUE) and the rainfall use efficiency (RUE)

6.1 Introduction

WUE is defined as the level of grain yield/biomass per unit of water used by a crop, while the RUE is defined as the amount of grain yield/biomass produced per amount of rainfall (Hatfield et al., 2001). WUE and RUE are closely related due to the fact that both parameters are dependent of soil water storage.

Both Musick et al. (1994) and Good and Smika (1978) found a positive relationship between soil water stored at planting and yield. According to these researchers the relationship is more significant compared to a relationship to seasonal water use. Therefore, soil surface modifications, for example, through tillage or surface mulching may result in increases in soil water storage during fallow or periods of low rainfall.

The WUE and RUE was calculated for each treatment combination from the water balances attached in Chapter 5 and yield parameters. The WUE was determined by means of *Equation 1*, while the RUE was determined by means of Hensley, Snyman and Potgieters (1990) *Equation 2*. For the 2014 growing season canola and wheat yield, WUE and RUE are presented and discussed, while for the 2015 growing season canola, wheat and medic yield, WUE and RUE are presented and discussed.

6.2 2014 Growing season

6.2.1 Final grain yield

Wheat after canola in a LWCW system

The highest final grain yield was obtained for the DT treatment (3802.0 kg.ha^{-1}) while the lowest final grain yield was obtained for the NT treatment (3656.1 kg.ha^{-1}). Similar results were obtained by Hoffman (1990) who found that CT practices result in higher grain yield compared to NT. A final grain yield of 3799.8 kg.ha^{-1} was obtained for the MP treatment. No significant difference (P = 0.0421) in final grain yield was found between tillage treatments for the LWCW system *(Table 6.1).* The grain yield results obtained correlate with results obtained by Unger (1994) who similarly found no significant difference in wheat yield between tillage treatments. Halvorson et al., (2002) investigated the effect of different crop rotation systems and soil disturbances on winter wheat yield and soil carbon in the Central Great Plain, but found no significant difference in wheat yield between treatments. The grain yield results however disagree with results obtained by Wiese (2013) who concluded that tillage and crop rotation systems affected grain yield significantly.

Canola after wheat in a WLWC system

The grain yield for the MP treatment (2131.2 kg.ha^{-1}) was the highest for the WLWC system. A final grain yield of 2043.6 kg.ha^{-1} was obtained for the DT treatment and a final yield of 1913.1 kg.ha^{-1} for the NT treatment. No significant difference (P = 0.0649) in final grain yield was found between tillage treatments for the WLWC system *(Table 6.1).*

Wheat after medic in McWMcW system

For this particular system the highest final grain yield was obtained for the NT treatment (4066.0 kg.ha^{-1}) while the lowest grain yield was obtained for the MP treatment (3925.4 kg.ha^{-1}). The wheat yield results can be compared with results found by Mrabet (2002) who reported higher yields under NT. The higher yield under NT was ascribed to increased residue cover (Mrabet, 2002). The final grain yield for the DT treatment was 3887.9 kg.ha^{-1} respectively. No significant difference (P = 0.2654) in final grain yield was observed between all treatments in the McWMcW system *(Table 6.1)* (Unger, 1994; Halvorson et al., 2002). Higher yields were obtained for all treatments for this particular system compared to previous mentioned crop rotation systems. Higher yields obtained may be ascribed to a nitrogen effect of the previous medic crop year.

6.2.2 Water use efficiency (WUE) and rainfall use efficiency (RUE)

Water use efficiency was expressed as the total grain yield produced per mm ET, while RUE was expressed as the total grain yield produced per mm rainfall.

Wheat after canola in a LWCW system

The WUE and RUE for the wheat after canola system is summarized in *Table 6.1*. Although no significant differences were found in WUE and RUE values (P = 0.4991); (P < 0.0001) the NT treatment resulted in the highest WUE value of 10 kg.ha $^{-1}$.mm^{-1} while the DT treatment resulted in the highest RUE value of

13.7 kg.ha $^{-1}$.mm^{-1}. Results obtained by Swiegelaar (2013) on the same soils at the Langgewens Research Farm similarly found that CT systems result in higher RUE compared to NT. Hoffman (1990) also reported that CT result in higher RUE compared to NT. No significant difference was found in yields (P = 0.05) for all treatments in this system and therefore the conclusion was made that the NT treatment made the most efficient use of the available water when considering evaporation and transpiration parameters. These results can be substantiated by results obtained by Jin et al., (2007) who also concluded that NT systems result in a higher WUE compared to CT systems, although no significant difference was found.

Canola after wheat in a WLWC system

The WUE and RUE for the canola after wheat system is summarized in *Table 6.1.* The NT treatment resulted in the lowest WUE and RUE. The WUE for the NT treatment was respectively 6.1 kg.ha.mm^{-1} and the RUE 6.9 kg.ha.mm^{-1}. The MP treatment resulted in the highest WUE (7.5 kg.ha.mm^{-1}) and RUE (7.7 kg.ha.mm^{-1}), followed by the DT treatment with values of 6.5 kg.ha.mm^{-1} (WUE) and 7.3 kg.ha.mm^{-1} (RUE). No significant difference was found in RUE values between tillage treatments (P = 0.05).

Wheat after medics in a McWMcW system

The WUE and RUE for the wheat after medic system is summarized in *Table 6.1.* Again the MP treatment showed the highest WUE with a value of 12.6 kg.ha.mm^{-1}, while the NT treatment showed the highest RUE with a value of 14.6 kg.ha.mm^{-1}. Therefore, due to the fact that there was no significant difference in yields (P = 0.0005) for all treatments in this system, the MP treatment made most efficient use of the available water when taking only evaporation and transpiration parameters into consideration. No significant difference in WUE and RUE values were observed between tillage treatments in the McWMcW system (P = 0.2557); (P =0.05).

Table 6.1: Yield, ΣET, WUE and RUE under different crop rotation systems and tillage treatments at the end of the 2014 growing season at Langgewens

ROTATION SYSTEM	TILLAGE TREATMENT	GRAIN YIELD (KG/HA^{-1})	ΣET (MM)	WUE (KG/HA/MM^{-1})	RUE (KG/HA/MM^{-1})
LWCW	NT	3656.1 a	363.8 a	10.0 a	13.1 a
LWCW	MP	3799.8 a	399.9 a	9.5 a	13.6 a
LWCW	DT	3802.0 a	386.8 a	9.8 a	13.7 a
WLWC	NT	1913.1 a	311.3 a	6.1 a	6.9 a
WLWC	MP	2131.2 a	283.3 a	7.5 a	7.7 a
WLWC	DT	2043.6 a	313.8 a	6.5 a	7.3 a
McWMcW	NT	4066.0 a	394.6 a	10.3 a	14.6 a
McWMcW	MP	3925.4 a	310.9 b	12.6 a	14.1 a
McWMcW	DT	3887.9 a	334.2 b	11.6 a	14.0 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

6.3 2015 Growing season

6.3.1 Final grain yield for wheat and canola and final biomass for medics

Canola after wheat in a WLWC system

Although not significant, the highest final grain yield was obtained for the MP treatment (1529.4 kg.ha^{-1}) while the lowest final grain yield was obtained for the DT treatment (1409.9 kg.ha^{-1}) (P = 0.8078). A final grain yield of 1415.9 kg.ha^{-1} was obtained for the NT treatment. No significant differences (P = 0.8078) in final grain yield were found between tillage treatments for the WLWC system *(Table 6.4).*

Wheat after lupine in a CWLW system

For this particular system a significantly higher grain yield was obtained for the NT (2264.7 kg.ha^{-1}) treatment compared to both the MP (2004.7 kg.ha^{-1}) and DT treatments (2108.3 kg.ha^{-1}), while no significant difference was found between the DT and MP treatments (P = 0.0274) *(Table 6.4).* Mrabet (2002) similarly reported higher wheat grain yields under NT. The higher yield was ascribed to the increased residue cover in the NT treatment. The grain yield results obtained is in contrast with results obtained by Unger (1994) and Halvorson et al. (2002) who found no significant difference in wheat yield between tillage treatments.

Medic after wheat in a WMcWMc system

Biomass results were considered as total yield results at the end of the growing season due to a different harvesting technique compared to wheat and canola. Although no significant difference was found in biomass between tillage treatments (P = 0.9010), the lowest biomass was obtained for the MP treatment. Lower biomass after a MP inversion tillage action was expected as medic seeds were transported to deeper soil layers and therefore resulted in seedling emergence delays and in some cases unsuccessful seedling emergence (*Figure 6.2*). Therefore, smaller crops and lower crop densities was observed for medics throughout most part of the growing season. Wiese (2013) similarly found that tillage did not affect total biomass production. The results obtained however contradict results found by Hemmat and Eskandari (2006) and Rieger et al. (2008) who concluded that no-tillage treatments tend to produce more biomass compared to CT treatments.

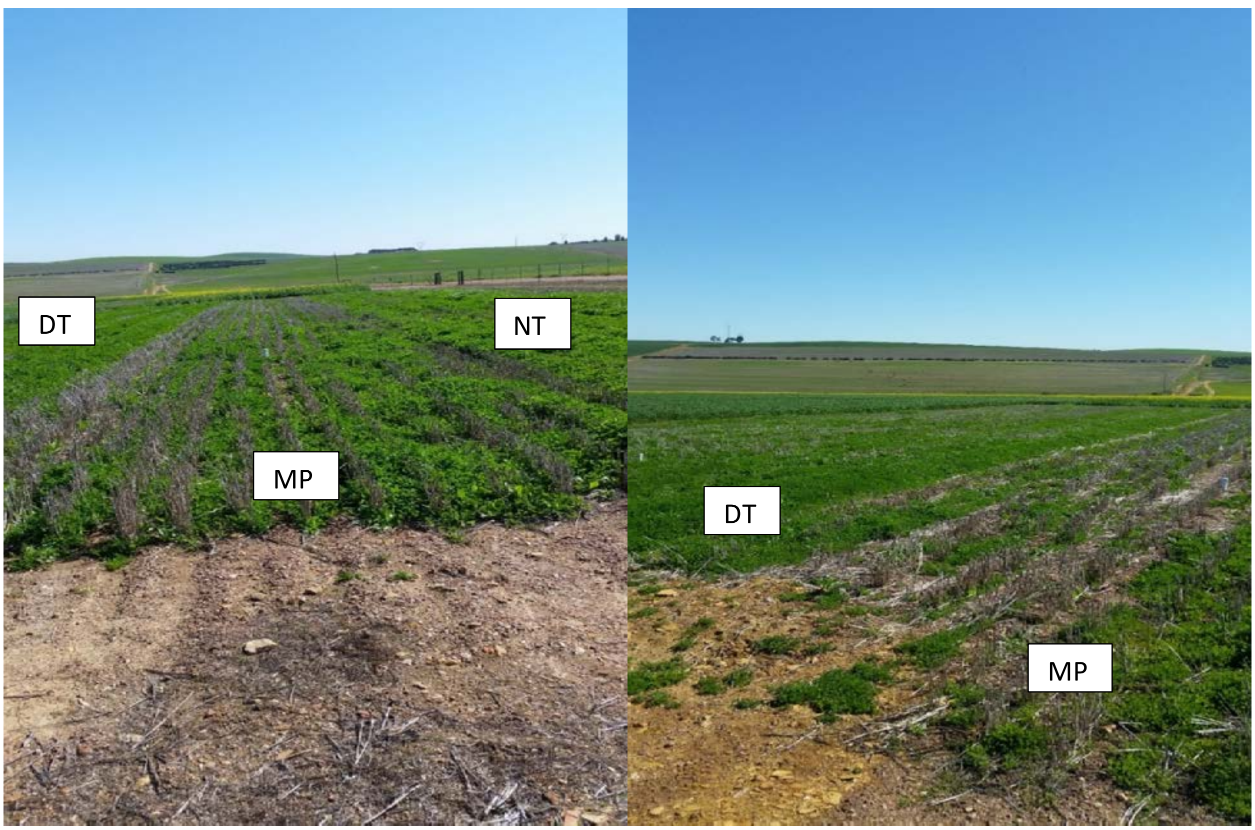


Figure 6.1: Digital images of different tillage treatments (NT, MP, DT) for medics at Langgewens 2015

6.3.2 Water use efficiency (WUE) and rainfall use efficiency (RUE)

Water use efficiency was expressed as the total grain yield produced per mm ET, while RUE was expressed as the total grain yield produced per mm rainfall.

Canola after wheat in a WLWC system

The WUE and RUE for the canola after wheat system is summarized in *Table 6.3*. Although no significant differences were found in WUE and RUE values (P = 0.9618; P = 0.8184) both the highest WUE and RUE values were observed for the MP treatment (7.9 kg.ha.mm^{-1}; 9.0 kg.ha.mm^{-1}). No significant difference was found in grain yields (P = 0.05) for all treatments in this particular system and therefore the conclusion was made that the DT treatment made the most efficient use of the available water when considering evaporation and transpiration parameters. These results are however in contrast with results obtained by Jin et al., (2007) who concluded that NT systems result in higher WUE compared to CT systems.

Wheat after lupin in a CWLW system

The WUE and RUE for the wheat after lupine system is summarized in *Table 6.3*. The highest WUE value was observed for the DT treatment (11.6 kg.ha.mm^{-1}) while the highest RUE value was observed for the NT treatment (13.4 kg.ha.mm^{-1}). No significant difference was found in WUE and RUE values between all tillage treatments tested (P = 0.2084; P = 0.1508).

Medic after wheat in a WMcWMc system

The WUE and RUE for the medic after wheat system is summarized in Table 6.3. Although not significantly different (P = 0.8630), the highest WUE was observed for the DT treatment (12.1 kg.ha.mm^{-1}) shortly followed by the NT treatment (11.6 kg.ha.mm^{-1}). The lowest WUE was obtained for the MP treatment (7.6 kg.ha.mm^{-1}). No significant difference in RUE was observed between tillage treatments (P = 0.9010). The same trend was observed for RUE as for WUE with the highest RUE observed for the DT treatment (13.4 kg.ha.mm^{-1}), shortly followed by the NT treatment (11.5 kg.ha.mm^{-1}) while the lowest RUE was obtained for MP (9.5 kg.ha.mm^{-1}).

Table 6.2: Yield, ΣET, WUE and RUE under different crop rotation systems and tillage treatments at the end of the 2015 growing season at Langgewens

ROTATION SYSTEM	TILLAGE TREATMENT	FINAL YIELD/BIOMASS (KG/HA^{-1})	ΣET (MM)	WUE ($KG/HA/MM^{-1}$)	RUE ($KG/HA/MM^{-1}$)
WLWC	NT	1415.9 a	203.1 a	7.0 a	8.4 a
WLWC	MP	1529.4 a	194.6 a	7.9 a	9.0 a
WLWC	DT	1409.9 a	206.3 a	6.8 a	8.3 a
CWLW	NT	2264.7 a	201.5 a	11.2 a	13.4 a
CWLW	MP	2004.7 b	192.3 a	10.4 a	11.9 a
CWLW	DT	2108.3 b	181.1 a	11.6 a	12.5 a
WMcWMc	NT	1946.7 a	170.2 b	11.6 a	11.5 a
WMcWMc	MP	1609.7 a	226.0 a	7.6 a	9.5 a
WMcWMc	DT	2255.4 a	186.3 ab	12.1 a	13.4 a

WLWC: canola after wheat, LWCW: wheat after canola, McWMcW: wheat after medics

Note 1: Biomass results ($kg.ha^{-1}$) are indicative of the total yield for medics

Note 2: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

6.4 Conclusion

In the 2014 growing season no significant differences were found between all tillage treatments and crop rotation systems investigated while for the 2015 growing season NT resulted in a significantly higher wheat yield compared to both DT and MP in the CWLW system which was attributed to the crop residues present. Although the lowest biomass was obtained for the MP treatment no significant difference between treatments were observed in biomass results for medics. The lower biomass under medics were contributed to the transportation of the self-regenerating medic seeds during the inversion plough action which resulted in seedling emergence delays and poor crop stand. When comparing the 2014 and 2015 grain yield results a 71% decrease in canola yield was observed while a 57% decrease in wheat grain yield was observed in the 2015 growing season. Even though the crops underwent a longer growing season during 2015 a total of 31% less rainfall was recorded during the 2015 growing season compared to the 2014 growing season and therefore lower grain yields were expected. Once-off tillage had no significant effect on WUE and RUE in both the 2014 and 2015 growing seasons for all tillage treatments and crop rotation systems tested.

Chapter 7: Conclusions and recommendations

7.1 Conclusions and recommendations

Global food security poses a huge challenge on sustainable food production. The conversion to conservation agriculture has become vital as it can improve physical, chemical and water related properties of the soil and thereby advance global food security. Previous studies have however shown that CA may result in negative secondary effects and therefore increased interest in strategic tillage has arose. The first objective of the study was to examine the effect of once-off tillage of no-till soil on both soil physical and chemical properties. A further aim of the study was to examine the effect of once-off tillage on the soil water balance in order to determine the efficiency of water use by crops included in the study.

It was concluded that the once-off tillage action had no effect on particle size distribution as few significant differences that showed no pattern were found. Therefore, the fact that soil texture is an inherent soil property and cannot be changed by tillage and crop rotation supports the results obtained during the study. Tillage had no significant effect on coarse fragment % in both wheat systems investigated, although a significantly higher coarse fragment % was observed for DT in the canola system. This result was however only observed in the 200-300 mm soil depth. The general coarse fragment percentage trend observed was an increase with soil depth. The coarse fragment % results were not indicative of a mechanical sieving action which is usually only expected after the repeatable conduction of conventional tillage practices.

DT was the only treatment to result in significant aggregate stability decreases in both the WLWC and LWCW crop rotation systems. In both the 0-100 mm and 300-400 mm soil depth a significantly higher aggregate stability was observed for the NT treatment compared to the DT treatment. The aggressive mechanical action of the deep tine implement was responsible for the aggregate stability decrease. Aggregate stability decreased with depth and therefore results correlated with SOC results due to increases in aggregate stability percentages at soil depths where increases in SOC were observed.

The macro-aggregate density results are not indicative of the effect of the once-off tillage action. Undisturbed clods were sampled which formed during the breakdown of the soil structure during tillage. Therefore, it was concluded that the clods were not affected by the tillage action as high macro-aggregate density values were observed which was ascribed to the natural undisturbed soil structure formed during the 7 years of no-tillage. Other methods of bulk density measurement must be applied. Sample clods were digitally scanned through X-ray diffraction and promising results, although repetitions were not obtained, were found. Future research must also make sure that bulk density measurements are taken right after tillage due to soil conditions turning back to original conditions as found before tillage.

Hydraulic conductivity showed significant differences between treatments. Although not always significant, both the NT and DT treatments showed the highest hydraulic conductivity compared to MP for all cropping systems investigated (P = 0.05). The increase in hydraulic conductivity for the DT treatment can be explained by a more favourable soil structure created by the rip action, while the increase under NT was contributed to the preservation of soil macro-pores which is formed by earthworms and decayed plant roots as well as the present mulch layer. A MP tillage action leaves a soil surface bare which exposes the soil surface to compacting effects of rainfall and soil resettlement. The Swartland soils are known as hard-setting soils, therefore due to infiltration rates measured after big rainfall events which allowed particle resettlement to take place at the soil surface and result in crust formation, the infiltration rates were not regarded as representative of the soil infiltration rates after tillage

The general trend was an increase in pH (KCl and H_2O) with depth. Although significant differences were observed it was not attributed to a tillage effect but rather to the inherent mother material properties. The high pH in the shale layer (300-400 mm) was contributed to the fact that mother materials have a high base status. A decreasing trend with soil depth was observed for electrical conductivity. DT proved to be the least favourable in terms of the leaching of salts due to EC increases while NT proved to be the most favourable.

The SOC content was not influenced by the single tillage operation as no significant differences were observed between all tillage treatments at all measured depths. The highest SOC content was observed in the 0-100 mm soil depth where after SOC decreased with depth. The higher SOC content in the 0-100 mm soil layer was ascribed to the present crop residues. No significant difference was found between treatments in the 0-100 mm soil depth and therefore it was concluded that the conventional tillage actions did not transport the crop residues to deeper soil layers as was expected.

Active C is a C pool that is easily decomposed by soil microbes and is easily lost and mostly affected through tillage in the short term when comparing humified fractions. Therefore, it was expected that the active C content would decrease after a tillage event. The Active C content was however not significantly influenced by a once-off tillage operation in 2014 due to coherent soil conditions which did not allow active microorganism activity. In 2015 (1 year after tillage) a significant increase in active C content was observed for DT for both the medic after wheat and the wheat after canola systems which was explained by an increase in microbe activity due to favourable soil conditions.

Tillage had no effect on SWC as significant differences in SWC were only observed on 30 July, 22 and 27 October for the wheat after canola system during the 2014 growing season. Significant differences were observed between NT and DT after big rainfall events and at the end of the growing season. SWC readings in 2014 ranged between 35-270 mm for all tillage treatments and crop rotation systems measured. No conclusion regarding the tillage treatment capable of storing the highest amount of water could be made as different trends were observed for different treatments and crop rotation systems. ET values varied according to the crops developing stage as well as the available SWC and external environmental factors (rainfall and temperature). Tillage had no significant effect on ET as no significant difference in ΣET was observed at the end of the 2014 growing season. No trend regarding the tillage treatment capable of storing the most amount of water was observed during the 2014/2015 fallow season as different treatments resulted in a higher SWC for each crop rotation system. More valuable results would have been obtained during the fallow season if technical difficulties could have been overcome.

The total amount of rainfall recorded during the 2015 growing season was 31% lower compared to rainfall recorded during 2014 and therefore SWC readings during the 2015 growing season ranged between 10-140 mm which is much lower compared to the 36-269 mm recorded during 2014. In 2015 MP tended to result in the highest SWC for all crop rotation systems and on several dates significantly higher SWC readings were observed for MP compared to NT and DT. Data was further inspected by separating the 0-400 mm soil depths from the 400-800 mm soil depths. Significantly higher soil water contents were observed for the 400-800 mm soil depth on most measured dates during the 2015 growing season ($P < 0.0001$). Thorough inspection of data showed that porosity may have increased after the application of a MP tillage action. Another explanation was the fact that crops did not make efficient use of the available water in the 0-400 mm soil depth. The lateral movement of soil water through the shale layer may also have contributed to the increase in SWC observed in the deeper soil layers (400-800 mm). Due to scarcity of research on the soil water balance topic a definite conclusion regarding the higher SWC under MP could not be drawn. MP resulted in a significantly higher ΣET at the end of the 2015 growing season for the WMcWMc system. The latter result was attributed to a higher evaporation demand during the dry 2015 growing season due to low crop densities and lower crop stands which led to more soil surface exposure.

In the 2014 growing season no significant differences were found in yield between all tillage treatments and crop rotation systems investigated. In contrast in the 2015 growing season NT resulted in a significantly higher wheat yield compared to both DT and MP in the CWLW system which was attributed to the crop residues present. No significant differences between treatments were observed in biomass results for medics (P = 0.9010). The lower biomass under medics was contributed to the transportation of the self-regenerating medic seeds during the inversion plough action which resulted in seedling emergence delays and poor crop stand. When comparing the 2014 and 2015 grain yield results a 71% decrease in canola yield was observed while a 57% decrease in wheat grain yield was observed in 2015. Even though the crops underwent a longer growing season during 2015 a total of 31% less rainfall was recorded during the 2015 growing season compared to the 2014 growing season and therefore lower grain yields were expected. Once-off tillage had no significant effect on WUE and RUE in both the 2014 and 2015 growing seasons for all tillage treatments and crop rotation systems tested.

Not only does the effect of the tillage action on the soil physical, chemical and water related properties play a role in the decision making of conducting once-off tillage, but also does the financial aspects behind the tillage action. For a once-off tillage action to be viable positive results regarding soil quality and productivity must be realized. In general the once-off tillage action had no significant effect on soil physical, chemical and water related properties as well as crop performance and therefore it will not be financially viable to conduct a once-off tillage action due to the cost of tillage. It must be taken into consideration that the results obtained is only representative of the soil and climate conditions present at Langgewens.

Research on the application of conservation agriculture in South Africa is relatively new and therefore further research is necessary to build a strong scientific database. This would greatly contribute in facilitating the effect of different crop rotations under no-tillage on SOC in different climate and soil types. Research on the effect of once-off tillage has never been investigated in South Africa and therefore it will greatly assist as a decision making tool for farmers. There is consequently a gap in knowledge on the effect of strategic tillage on selected soil properties and therefore future research on the topic in other dryland grain producing areas will greatly benefit.

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Appendix A: Soil classification and profile description

Table 1:

Profile number:	1	Aspect:	North West
Co-ordinates:	33016’24.2”S/18042’29.2”E	Terrain unit:	Mid-Slope
Soil form:	Glenrosa	Altitude:	197m
Soil family:	Bisho (2211)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None

Slope form: Convex

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; gravel: 2-6 mm common; few roots visible; transition abrupt and clear tonguing.	Orthic
B	300-900	Dry colour: very pale brown 10 YR 7/4; moist colour: yellowish brown; structure: weak, fine, angular, blocky, more than 40% clay; consistency: hard in wet and dry state; many coarse shale fragments 6-25 mm and 25-75 mm.	Lithocutanic

Table 2:

Profile number:	2	Aspect:	North West
Co-ordinates:	33016'26.7"S/18042'27.2"E	Terrain unit:	Upper mid-slope
Soil form:	Glenrosa	Altitude:	195m
Soil family:	Overberg (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	3%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0-250	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; gravel: 2-6 mm common; few roots visible; transition gradual and smooth.	Orthic
A2	250-400	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10YR 4/4; structure: massive, apedal, 5-10% clay; coarse gravel 8-25 mm very common; few roots visible; transition abrupt and tonguing clear to observe.	Orthic/E
B	400-900	Dry colour: very pale brown 10 YR 7/4; moist colour: yellowish brown 10 YR 5/6; structure: weak, fine, angular, blocky, more than 40% clay; consistency: hard in wet and dry state and have some degree of stickiness and plasticity when wet; 25-50% clay cutans visible; distinct black and brown geogenic mottling common; many coarse shale fragments 8-25 mm; no roots observed.	Lithocutanic

Table 3:

Profile number:	3	Aspect:	North West
Co-ordinates:	33016’29.4”S/18042’22.4”E	Terrain unit:	Upper mid-slope
Soil form:	Glenrosa	Altitude:	186m
Soil family:	Overberg (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None

Slope form: Convex

Slope: 2-3%

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive apedal, 15-25 % clay; consistency: hard in wet and dry state; 15-25% gravel in 2-6 mm common; few roots visible; transition gradual and smooth.	Orthic
A2	300-400	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: apedal, 10% clay; consistency: hard in wet and dry state; 50-90% gravel in 2-6 mm; coarse gravel in 6-25 mm; few visible roots; transition abrupt and smooth.	Orthic/E
B1	400-600	Dry colour: very pale brown 10 YR 7/4; moist colour: yellowish brown 10 YR 5/6; structure: moderate fine, blocky, more than 45% clay; coarse black and brown geogenic mottles common; clay cutans common; transition gradual and smooth.	Pedocutanic
B2	600-900	Dry colour: brownish yellow 10 YR 5/6; moist colour: brownish yellow 10 YR 6/8; structure weak fine angular blocky; consistency: hard in wet and dry state; no roots observed.	Lithocutanic

Table 4:

Profile number:	4	Aspect:	North West
Co-ordinates:	33016’23.5”S/18042’26.3”E	Terrain unit:	Mid-slope
Soil form:	Glenrosa	Altitude:	195m
Soil family:	Overberg (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	5%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; 15-25% gravel in 2-6 mm common; few roots visible; transition gradual and smooth.	Orthic
A2	300-450	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: apedal, 5-10% clay; consistency: hard in wet and dry state; 50-70% gravel in 2-6 mm; few visible roots; transition abrupt and tonguing.	Orthic/E
B	450-900	Dry colour: brownish yellow 10 YR 5/6; moist colour: brownish yellow 10 YR 6/8; structure: moderate, fine, angular, blocky, more than 45% clay; coarse black and brown geogenic mottles common; consistency: hard in wet and dry state and have some degree of stickiness and plasticity; clay cutans commonly visible; many shale fragments 6-25 mm; no roots observed.	Lithocutanic

Table 5:

Profile number:	5	Aspect:	North West
Co-ordinates:	33016’23.2”S/18042’23.7”E	Terrain unit:	Mid-slope
Soil form:	Glenrosa	Altitude:	192m
Soil family:	Bisho (2211)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	5%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; coarse gravel 6-25 mm common; few roots visible; transition abrupt and tonguing.	Orthic
B	300-900	Dry colour: very pale brown 10 YR 7/4; moist colour: yellowish brown 10YR 5/6; structure: weak, fine, angular, blocky, more than 40% clay; consistency: hard in wet and dry state; distinct black and brown geogenic mottling common; many coarse shale fragments 6-25 mm and 25-75 mm; no roots observed.	Lithocutanic

Table 6:

Profile number: 6

Co-ordinates: 33016’25.7”S/18042’21.7”E

Soil form: Glenrosa

Soil family: Overberg (2111)

Underlying parent material: Shale

Slope form: Convex

Slope: 2-3%

Aspect: North West

Terrain unit: Upper mid-slope

Altitude: 189m

Surface coarse fragments: 30-65%

Wetness: None

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; 15-25% gravel 2-6 mm; few visible roots; transition abrupt and show some degree of tonguing.	Orthic
B	300-900	Dry colour: very pale brown 10 YR 7/4; moist colour: yellowish brown 10YR 5/6; structure: weak, fine, angular, blocky; consistency: hard in wet and dry state with some stickiness and plasticity when wet; few black and brown geogenic mottles; 50-90% coarse shale fragments; few roots observed; transition abrupt with tonguing.	Lithocutanic
R	900-1000	Hard rock	Shale

Table 7:

Profile number:	7	Aspect:	North West
Co-ordinates:	33016’31.6”S/18042’17.6”E	Terrain unit:	Lower mid-slope
Soil form:	Swartland	Altitude:	180m
Soil family:	Adelaide (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	2%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; 15-25% gravel 2-6 mm; few visible roots; transition abrupt and show some degree of tonguing.	Orthic
B1	300-800	Dry colour: brownish yellow 10 YR 6/6; moist colour: brownish yellow 10YR 6/8; structure: moderate fine, angular, blocky, 40-45% clay; consistency: hard in wet and dry state with some stickiness and plasticity when wet; black and brown cutans common; common gravel 2-6 mm; few roots observed; transition abrupt and tonguing clear to observe.	Pedocutanic
B2	800-1000	Dry colour: brownish yellow 10 YR 5/6; moist colour: brownish yellow 10YR 6/8; structure: moderate fine, angular, blocky; consistency: hard in wet and dry state; no roots observed.	Lithocutanic

Table 8:

Profile number:	8	Aspect:	North West
Co-ordinates:	33016’31.5”S/18042’23.9”E	Terrain unit:	Lower mid-slope
Soil form:	Swartland	Altitude:	185m
Soil family:	Adelaide (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	1-2%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0-200	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; gravel: 2-6 mm common; few roots visible; transition gradual and smooth.	Orthic
A2	200-350	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10YR 4/4; structure: massive, apedal, 10% clay; few gravel 2-6 mm with coarse gravel 8-25 mm common; few roots visible; transition abrupt and tonguing clear to observe.	Orthic/E
B	350-900	Dry colour: brownish yellow 10 YR 6/6; moist colour: brownish yellow 10 YR 6/8; structure: moderate fine, angular, blocky with more than 45% clay; consistency: hard in wet and dry state and have some degree of stickiness and plasticity when wet; 25-50% clay cutans visible; no roots observed.	Pedocutanic

Table 9:

Profile number:	4	Aspect:	North West
Co-ordinates:	33016’33.3”S/18042’20.4”E	Terrain unit:	Lower mid-slope
Soil form:	Swartland	Altitude:	182m
Soil family:	Adelaide (2111)	Surface coarse fragments:	30-65%
Underlying parent material:	Shale	Wetness:	None
Slope form:	Convex		
Slope:	1%		

Horizon	Depth (mm)	Description	Diagnostic horizon
A1	0-300	Dry colour: very pale brown 10 YR 7/3; moist colour: dark brown 10 YR 4/4; structure: massive, apedal, 10-15 % clay; consistency: hard in wet and dry state; 15-25% gravel: 2-6 mm; few roots visible; transition abrupt and smooth.	Orthic
A2	300-600	Dry colour: brownish yellow 10 YR 6/6; moist colour: brownish yellow 10YR 6/8; structure: moderate fine angular blocky; consistency: hard in wet and dry state and have some degree of stickiness and plasticity; few gravel 2-6 mm; few roots visible; transition abrupt and tonguing clear to observe.	Pedocutanic
B	600-900	Dry colour: brownish yellow 10 YR 5/6; moist colour: brownish yellow 10 YR 6/8; structure: moderate fine, angular, blocky, more than 45% clay; consistency: hard in wet and dry state; no roots observed.	Lithocutanic

Appendix B: Soil water balance sheets of different crop rotation systems under different tillage treatments throughout the 2014 growing season at Langgewens

Table 10: The effect of NT on the soil water balance of a McWMcW cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	16.3	18.6	19.3	19.5	14.6	17.2	21.0	17.5	18.0	16.4	10.2	6.5	4.3	3.4	2.8	2.4
20cm	16.9	25.7	25.4	25.5	15.6	15.3	27.2	15.6	16.0	15.3	11.2	7.5	5.2	4.7	4.4	3.9
30cm	7.5	13.8	16.6	16.0	10.7	10.9	25.2	11.2	11.2	12.2	9.6	6.0	4.5	3.7	3.6	3.4
40cm	13.3	19.2	20.2	27.6	11.7	15.7	38.1	12.9	11.4	14.4	11.5	7.2	5.6	4.5	4.2	4.3
50cm	17.3	23.0	38.3	38.8	19.0	25.3	38.0	20.5	19.2	25.1	18.9	15.0	10.7	8.4	8.0	7.9
60cm	21.2	33.3	38.9	39.1	24.9	38.5	39.5	31.0	24.7	32.9	23.0	21.1	17.1	11.7	10.9	10.8
70cm	26.0	38.5	40.2	40.2	33.9	39.7	40.4	35.0	33.3	36.4	20.7	18.4	16.0	10.2	9.3	9.2
80cm	35.6	39.4	39.7	39.6	31.1	39.7	39.9	31.7	32.1	33.0	25.6	21.9	19.6	14.7	12.9	12.6
Total	154.0	211.3	238.6	246.3	161.4	202.2	269.5	175.4	166.0	185.6	130.6	103.6	82.9	61.3	56.0	54.5
ΔS		-57.3	-27.2	-7.7	85.0	-40.9	-67.3	94.2	9.3	-19.5	54.9	27.0	20.7	21.6	5.3	1.5
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1	10.4	1.6	4.8	0	0
U		7.9	8.4	0.0	0.0	24.1	43.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		0.0	0.0	8.5	86.6	0.0	0.0	108.8	34.1	7.9	55.9	37.4	22.3	26.4	5.3	1.5
ET/day		0.0	0.0	0.9	9.6	0.0	0.0	7.8	2.6	1.0	8.1	3.1	2.8	1.7	0.8	0.3
ΣET		0.0	0.0	8.5	95.0	95.0	95.0	203.8	237.9	245.8	301.7	339.1	361.4	387.8	393.1	394.6

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 11: The effect of a once-off MP treatment on the soil water balance of a McWMcW cropping system during the 2014 growing season at Langgewens Research Farm.

Date / Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	10.8	13.3	13.4	13.7	12.1	13.7	15.6	15.2	17.9	15.5	11.9	8.6	5.0	3.6	2.8	2.4
20cm	13.1	15.9	19.8	20.7	16.1	17.6	19.7	17.9	17.7	18.3	15.4	11.7	6.9	5.1	4.8	4.5
30cm	16.9	20.5	19.8	20.2	17.7	17.3	20.1	17.6	17.7	18.7	15.8	12.2	7.4	5.6	5.4	5.3
40cm	15.8	18.2	25.1	26.0	16.2	16.5	24.6	16.1	15.7	16.8	14.3	11.3	6.7	5.2	5.1	5.0
50cm	20.0	30.4	30.3	30.2	20.2	28.5	30.7	21.9	22.7	22.9	19.2	15.1	11.5	8.4	8.0	8.0
60cm	20.7	29.1	29.4	30.6	25.0	29.7	36.0	27.9	26.6	32.0	21.6	18.5	13.4	10.9	10.4	10.3
70cm	24.3	33.0	38.0	38.3	32.5	32.5	37.9	30.0	27.1	34.4	27.1	24.6	20.1	17.0	16.0	15.7
80cm	32.2	33.0	38.0	38.2	33.5	33.3	37.6	33.9	34.1	35.6	34.2	32.5	28.0	22.5	21.4	20.7
Total	153.8	193.4	213.9	217.9	173.3	189.1	222.3	180.6	179.5	194.2	159.4	134.5	99.1	78.5	73.9	71.9
ΔS		-39.5	-20.6	-3.9	44.6	-15.8	-33.2	41.7	1.1	-14.7	34.7	24.9	35.5	20.6	4.5	2.1
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1	10.4	1.6	4.8	0	0
U		0.0	1.8	0.0	0.0	0.0	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		0.0	5.0	12.3	46.2	6.6	3.4	56.3	25.9	15.1	35.7	35.3	37.1	25.4	4.5	2.1
ET/day		0.0	0.7	1.2	5.1	0.8	0.5	4.0	2.0	1.9	5.2	2.9	4.6	1.7	0.7	0.4
ΣET		0.0	5.0	17.3	63.4	70.1	73.5	129.8	155.7	170.8	206.5	241.8	278.9	304.3	308.8	310.9

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 12: The effect of a once-off DT treatment on the soil water balance of a McWMcW cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	10.8	14.4	13.3	14.6	11.8	13.6	19.1	15.2	15.2	14.9	9.5	6.2	3.9	2.9	2.4	2.2
20cm	11.4	12.8	13.0	16.8	12.1	12.4	16.1	12.7	12.3	15.3	9.7	7.0	5.1	4.2	4.1	3.9
30cm	11.6	12.9	24.3	25.7	15.0	16.9	27.0	17.6	16.0	21.0	14.4	11.7	8.0	6.0	5.8	5.6
40cm	15.8	17.6	28.6	29.5	17.6	24.1	31.9	24.2	19.2	25.5	18.5	14.6	12.4	9.2	9.1	8.8
50cm	19.9	24.2	32.5	35.3	25.7	31.3	37.9	29.6	28.1	30.1	26.2	21.4	17.4	15.6	15.5	15.2
60cm	31.4	37.6	37.1	38.7	29.9	39.3	40.0	32.4	28.6	31.7	28.8	27.4	20.8	17.2	17.1	16.6
70cm	30.8	37.4	36.2	39.7	28.3	38.8	39.5	31.6	28.7	33.0	29.0	28.6	24.3	17.9	16.8	16.5
80cm	30.3	36.9	37.2	37.9	37.1	37.8	38.4	38.6	30.9	39.3	31.5	30.3	26.6	20.0	16.5	16.0
Total	162.1	193.8	222.3	238.3	177.6	214.2	249.9	201.9	179.0	210.7	167.7	147.2	118.5	93.0	87.3	84.8
ΔS		-31.8	-28.5	-16.0	60.7	-36.6	-35.7	48.0	22.9	-31.7	43.0	20.5	28.7	25.5	5.8	2.4
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1	10.4	1.6	4.8	0	0
U		0.0	9.7	0.0	0.0	19.8	11.9	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	0.0
ET		17.6	0.0	0.2	62.3	0.0	0.0	62.6	47.7	0.0	44.0	30.9	30.3	30.3	5.8	2.4
ET/day		2.2	0.0	0.0	6.9	0.0	0.0	4.5	3.7	0.0	6.4	2.6	3.8	2.0	0.9	0.5
ΣET		17.6	17.6	17.9	80.2	80.2	80.2	142.8	190.5	190.5	234.5	265.4	295.7	326.0	331.7	334.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 13: The effect of NT on the soil water balance of a WLWC cropping system during the 2014 growing season at Langgewens Research Farm.

Date / Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	14.6	16.7	15.4	14.7	11.7	14.2	15.8	12.0	16.4	8.1	7.3	6.4	4.5	3.1	2.8	2.5
20cm	12.5	13.1	12.6	12.4	11.7	11.5	11.9	10.1	11.6	7.7	7.2	5.9	4.4	3.7	3.3	3.1
30cm	6.5	6.0	6.5	6.1	5.0	5.4	9.1	6.5	5.8	8.4	5.1	3.8	2.9	2.2	2.1	2.0
40cm	10.4	14.7	21.7	10.2	9.0	9.2	13.4	9.1	9.3	12.6	7.8	5.8	4.6	3.7	3.5	3.5
50cm	9.8	22.8	29.6	12.2	11.0	12.1	20.9	12.6	12.1	12.1	11.8	9.2	7.5	6.3	6.1	6.0
60cm	23.3	28.3	29.9	21.9	17.2	18.0	22.6	17.6	16.4	15.6	15.6	12.0	10.1	8.8	8.7	8.6
70cm	27.9	32.6	36.2	23.8	17.9	19.9	22.5	20.3	18.7	26.8	18.2	13.9	11.5	9.9	9.9	9.8
80cm	36.1	37.0	37.2	32.9	24.4	28.4	32.6	25.9	24.0	33.3	23.1	17.8	14.3	11.9	11.7	11.7
Total	141.0	171.2	189.1	134.2	107.9	118.7	148.8	114.1	114.3	124.5	96.0	74.8	59.6	49.5	48.0	47.2
ΔS		-30.2	-17.9	54.9	26.3	-10.8	-30.1	34.7	-0.3	-10.2	28.5	21.2	15.2	10.1	1.5	0.8
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	0.0	0.0	0.0	0.0	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		19.2	0.9	71.1	27.9	6.0	0.0	49.3	24.5	17.2	29.5	31.6	16.8	14.9	1.5	0.8
ET/day		2.4	0.1	7.2	3.1	0.8	0.0	3.5	1.9	2.1	4.3	2.6	2.1	1.0	0.2	0.2
ΣET		19.2	20.1	91.2	119.1	125.1	125.1	174.4	199.0	216.2	245.7	277.3	294.1	309.0	310.5	311.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 14: The effect of a once-off MP treatment on the soil water balance of a WLWC cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	10.7	15.0	13.4	13.1	8.4	10.3	10.8	8.9	15.8	7.3	5.8	4.7	3.7	3.0	2.1	1.9
20cm	20.6	20.8	18.6	19.5	17.5	18.1	18.4	16.4	16.0	14.7	11.7	11.8	9.2	7.8	7.1	6.8
30cm	7.2	6.8	6.1	6.6	5.8	6.2	6.2	5.7	5.8	6.9	4.6	3.9	3.4	2.9	2.8	2.6
40cm	1.8	1.7	1.7	1.7	1.5	1.6	1.7	1.4	1.3	7.6	4.8	4.0	3.3	2.7	2.2	2.4
50cm	11.7	11.4	11.0	12.9	10.8	11.0	23.9	12.0	9.7	15.8	12.8	10.3	9.2	7.9	7.4	7.2
60cm	16.7	16.5	26.1	26.6	17.5	24.4	30.0	20.6	19.6	20.8	17.7	14.8	12.9	11.2	10.6	10.5
70cm	18.1	21.0	28.1	28.7	19.2	28.2	38.9	22.5	22.2	23.9	20.4	17.3	15.4	13.2	12.5	12.4
80cm	19.3	27.6	27.3	31.2	22.6	30.6	36.0	24.5	24.3	26.0	22.7	17.6	15.5	12.9	12.3	12.2
Total	106.1	120.9	132.3	140.3	103.5	130.3	166.0	112.0	114.8	123.0	100.5	84.2	72.5	61.5	57.1	56.0
ΔS		-14.8	-11.4	-8.0	36.8	-26.8	-35.8	54.0	-2.8	-8.2	22.5	16.3	11.7	11.0	4.4	1.2
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	0.0	0.0	0.0	10.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		34.6	7.4	8.2	38.4	0.0	0.0	68.6	22.0	19.2	23.5	26.7	13.3	15.8	4.4	1.2
ET/day		4.3	1.1	0.8	4.2	0.0	0.0	4.9	1.7	2.4	3.4	2.2	1.7	1.0	0.7	0.2
ΣET		34.6	42.0	50.2	88.6	88.6	88.6	157.2	179.3	198.4	221.9	248.7	262.0	277.7	282.1	283.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 15: The effect of a once-off DT treatment on the soil water balance of a WLWC cropping system during the 2014 growing season at Langgewens Research Farm.

Date / Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	15.8	17.5	15.0	15.2	11.1	13.4	14.2	11.3	10.6	7.8	5.2	4.5	3.1	3.6	3.0	2.7
20cm	9.2	9.6	8.3	8.6	6.4	7.3	7.5	6.5	7.2	6.2	4.3	3.6	2.8	2.5	2.2	2.1
30cm	11.6	12.0	10.7	10.8	8.2	9.3	9.5	8.4	7.1	6.5	4.6	3.6	2.8	3.1	2.9	2.8
40cm	14.9	16.6	14.1	13.6	12.6	13.2	13.9	11.9	10.7	11.7	8.9	6.8	5.6	5.6	5.3	5.1
50cm	19.8	21.9	21.4	22.4	18.3	19.2	21.3	19.1	14.3	16.0	13.3	9.6	8.1	9.7	9.3	9.0
60cm	25.2	30.8	30.4	30.7	27.4	23.7	30.2	23.2	17.0	18.2	16.5	12.5	10.4	13.2	13.0	12.7
70cm	28.9	29.6	28.7	29.5	30.8	28.5	30.3	26.1	20.4	21.8	19.5	14.0	11.7	13.6	13.4	13.1
80cm	33.2	32.7	32.6	32.5	29.7	30.8	32.2	26.3	20.7	22.0	19.5	13.8	10.8	12.5	12.0	12.0
Total	158.6	170.7	161.2	163.3	144.6	145.4	159.3	132.7	108.1	110.2	91.8	68.3	55.4	63.8	61.1	59.6
ΔS		-12.2	9.5	-2.1	18.7	-0.8	-13.9	26.5	24.7	-2.1	18.4	23.4	13.0	-8.5	2.7	1.5
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0
ET		37.2	28.3	14.1	20.3	16.0	9.9	41.1	49.5	25.3	19.4	33.8	14.6	0.0	2.7	1.5
ET/day		4.7	4.0	1.4	2.2	2.0	1.4	2.9	3.8	3.1	2.8	2.8	1.8	0.0	0.4	0.3
ΣET		37.2	65.6	79.7	99.9	116.0	125.9	167.0	216.5	241.8	261.2	295.0	309.6	309.6	312.3	313.8

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 16: The effect of NT on the soil water balance of a LWCW cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	9.0	11.7	10.9	11.4	8.0	10.3	12.8	10.7	12.0	9.7	6.5	4.7	3.0	2.0	1.8	1.6
20cm	12.5	13.3	12.9	13.1	11.0	11.7	13.5	10.9	10.7	9.9	7.4	5.8	4.4	3.5	3.2	3.1
30cm	9.8	11.6	10.9	12.4	9.2	11.2	25.3	11.0	10.7	13.7	10.6	7.3	5.6	4.1	3.8	3.6
40cm	11.6	13.9	18.7	27.9	16.7	26.6	33.7	17.8	13.2	18.6	13.5	9.0	6.0	4.6	4.3	4.4
50cm	14.0	16.1	30.2	30.5	27.1	30.1	43.8	30.4	21.3	32.0	18.8	14.6	10.8	7.1	6.6	6.7
60cm	12.3	22.6	29.6	27.9	26.7	27.9	41.1	27.5	25.6	34.9	24.8	20.0	16.2	9.6	9.0	9.2
70cm	8.1	16.3	41.3	33.8	25.4	33.0	41.7	32.4	27.4	35.3	19.8	16.7	13.6	8.8	8.0	8.2
80cm	15.7	21.4	39.4	39.6	34.3	38.9	39.4	37.9	37.4	40.1	33.7	23.3	20.5	13.9	12.8	12.7
Total	93.1	126.9	193.9	196.4	158.5	189.7	251.3	178.6	158.2	194.2	135.2	101.5	80.1	53.6	49.6	49.5
ΔS		-33.8	-67.1	-2.5	38.0	-31.2	-61.6	72.6	20.4	-36.0	59.0	33.7	21.4	26.5	4.1	0.1
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	48.3	0.0	0.0	14.4	37.8	0.0	0.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0
ET		15.6	0.0	13.7	39.6	0.0	0.0	87.2	45.2	0.0	60.0	44.1	23.0	31.3	4.1	0.1
ET/day		2.0	0.0	1.4	4.4	0.0	0.0	6.2	3.5	0.0	8.7	3.7	2.9	2.0	0.6	0.0
ΣET		15.6	15.6	29.3	68.9	68.9	68.9	156.1	201.3	201.3	261.3	305.4	328.4	359.7	363.7	363.8

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 17: The effect of a once-off MP treatment on the soil water balance of a LWCW cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	11.5	13.5	12.8	12.7	9.0	11.0	14.2	11.7	13.8	12.9	9.1	6.3	3.7	3.1	2.4	2.3
20cm	14.8	18.3	16.9	16.7	14.6	16.4	23.9	16.7	17.1	17.8	13.5	9.7	6.4	4.9	4.5	4.4
30cm	8.8	11.2	10.1	11.1	8.7	10.3	17.6	9.6	9.6	9.9	7.8	5.8	4.3	3.2	3.0	2.7
40cm	9.4	9.6	9.4	22.6	8.3	8.2	34.8	8.3	7.6	11.0	7.8	5.5	3.9	3.1	2.9	2.9
50cm	12.3	12.4	13.2	32.1	12.0	27.0	36.9	14.4	13.0	28.5	16.7	13.1	9.3	6.8	6.2	6.4
60cm	14.3	17.1	31.9	36.3	18.3	28.8	39.6	28.4	20.1	32.1	20.6	17.5	14.0	9.5	8.8	9.1
70cm	12.0	23.5	32.4	33.1	23.8	32.5	37.5	26.1	22.2	35.8	23.2	20.1	15.6	10.3	9.7	9.6
80cm	17.1	26.5	33.2	34.3	27.9	34.2	39.4	36.2	30.3	38.4	31.0	21.6	17.5	12.5	11.4	11.5
Total	100.1	132.2	159.8	198.9	122.5	168.3	243.8	151.5	133.7	186.3	129.6	99.6	74.6	53.4	48.9	49.1
ΔS		-32.1	-27.7	-39.1	76.4	-45.8	-75.4	92.2	17.8	-52.5	56.7	30.0	25.0	21.3	4.5	-0.2
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	8.9	22.9	0.0	29.0	51.6	0.0	0.0	25.1	0.0	0.0	0.0	0.0	0.0	0.2
ET		17.3	0.0	0.0	78.0	0.0	0.0	106.8	42.6	0.0	57.7	40.4	26.6	26.1	4.5	0.0
ET/day		2.2	0.0	0.0	8.6	0.0	0.0	7.6	3.3	0.0	8.4	3.4	3.3	1.7	0.7	0.0
ΣET		17.3	17.3	17.3	95.3	95.3	95.3	202.2	244.7	244.7	302.4	342.8	369.3	395.4	399.9	399.9

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Table 18: The effect of a once-off DT treatment on the soil water balance of a LWCW cropping system during the 2014 growing season at Langgewens Research Farm.

Date Depth	11-06-14	19-06-14	26-06-14	06-07-14	15-07-14	23-07-14	30-07-14	13-08-14	26-08-14	03-09-14	10-09-14	22-09-14	30-09-14	15-10-14	22-10-14	27-10-14
10cm	14.2	18.1	15.8	13.8	10.6	12.9	15.1	13.1	15.9	13.2	8.9	5.9	3.3	2.4	1.9	1.9
20cm	23.7	25.3	23.5	20.5	19.9	21.5	23.0	20.6	22.7	20.4	14.8	10.5	7.2	5.6	4.9	4.8
30cm	10.8	11.4	10.8	12.4	9.6	10.7	21.2	9.7	10.8	10.0	7.8	5.8	4.1	3.3	3.1	3.0
40cm	2.8	2.8	2.9	3.2	2.5	1.8	26.9	1.8	1.9	2.0	1.6	1.2	1.0	0.7	0.6	0.6
50cm	4.8	4.8	4.3	22.5	4.1	10.2	28.6	7.6	4.9	12.9	6.2	4.6	2.9	2.1	1.9	2.0
60cm	11.3	10.8	11.3	29.9	11.7	28.8	39.8	17.2	15.3	30.3	15.4	11.6	8.5	5.8	5.4	5.5
70cm	7.9	12.8	17.5	25.0	16.9	24.9	40.6	27.0	20.7	28.9	21.6	15.5	12.3	8.6	7.9	7.7
80cm	18.6	21.8	27.1	27.4	26.7	27.4	39.1	28.9	29.2	30.5	27.1	19.5	16.4	11.4	10.4	9.9
Total	94.1	107.8	113.3	154.7	102.1	138.3	234.3	125.9	121.4	148.1	103.4	74.7	55.7	39.8	36.2	35.4
ΔS		-13.7	-5.4	-41.5	52.7	-36.3	-95.9	108.4	4.5	-26.7	44.8	28.6	19.0	15.9	3.6	0.8
P		49.4	18.8	16.2	1.6	16.8	23.8	14.6	24.8	27.4	1.0	10.4	1.6	4.8	0.0	0.0
U		0.0	0.0	25.3	0.0	19.5	72.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		35.7	13.4	0.0	54.3	0.0	0.0	123.0	29.3	0.7	45.8	39.0	20.6	20.7	3.6	0.8
ET/day		4.5	1.9	0.0	6.0	0.0	0.0	8.8	2.3	0.1	6.6	3.2	2.6	1.4	0.5	0.2
ΣET		35.7	49.1	49.1	103.3	103.3	103.3	226.3	255.6	256.3	302.1	341.1	361.7	382.4	386.0	386.8

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water while blue cells indicate field capacity

Appendix C: Soil water balance sheets of different crop rotation systems under different tillage treatments throughout the 2014 fallow season at Langgewens

Table 19: The effect of a once-off NT treatment on the soil water balance of a McWMcW cropping system during the 2014 fallow season at Langgewens Research Farm.

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	1.3	1.3	1.0	1.1
20cm	1.9	2.0	1.9	2.2
30cm	1.2	1.9	1.9	1.9
40cm	1.6	1.8	1.9	1.8
50cm	3.9	4.3	4.4	4.3
60cm	4.8	4.9	5.1	5.0
70cm	4.9	5.6	5.9	5.5
80cm	7.9	8.0	8.2	7.6
Total	27.5	29.8	30.3	29.2
ΔS	27.5	-2.3	-0.4	1.0
P	21	18.4	0.0	20.0
U	0.0	0.0	0.4	0.0
E	48.5	16.1	0.0	21.0
E/day	1.3	0.2	0.0	0.3
ΣE	48.5	64.6	64.6	85.6

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: *Note 2: Red colored cells indicate the lowest boundary of plant available water*

Table 20: The effect of a once-off MP treatment on the soil water balance of a McWMcW cropping system during the 2014 fallow season at Langgewens Research Farm.

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	2.8	3.5	2.6	3.5
20cm	4.0	4.2	4.0	3.8
30cm	5.0	5.1	5.0	4.7
40cm	4.6	4.6	4.6	4.4
50cm	4.6	5.8	5.8	5.7
60cm	8.9	9.3	9.2	8.6
70cm	9.8	11.6	11.5	10.6
80cm	13.5	12.6	12.3	11.0
Total	53.1	56.8	54.9	52.3
ΔS	53.1	-3.7	1.9	2.6
P	21	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	74.1	14.7	1.9	22.6
E/day	1.0	0.4	0.1	1.0
ΣE	74.1	88.8	90.7	113.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: *Note 2: Red colored cells indicate the lowest boundary of plant available water*

Table 21: The effect of a once-off DT treatment on the soil water balance of a McWMcW cropping system during the 2014 fallow season at Langgewens Research Farm.

Date **Depth**	04-12-14	11-02-15	05-03-15	11-05-15
10cm	1.8	1.3	1.0	1.5
20cm	1.9	1.3	1.2	1.6
30cm	3.1	2.6	2.1	2.8
40cm	4.8	2.7	2.5	3.3
50cm	7.0	4.3	4.1	5.6
60cm	9.1	6.1	5.4	7.1
70cm	6.9	5.3	5.0	6.7
80cm	6.6	5.5	5.7	5.8
Total	41.1	29.0	27.0	34.4
ΔS	41.1	12.1	2.1	-7.5
P	21	18.4	5.0	20.0
U	0.0	0.0	0.0	0.0
E	62.1	30.5	7.1	12.5
E/day	1.6	0.7	0.3	0.6
ΣE	62.1	92.6	99.6	112.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: *Note 2: Red colored cells indicate the lowest boundary of plant available water*

Table 22: The effect of a once-off NT treatment on the soil water balance of a LWCW cropping system during the 2014 fallow season at Langgewens Research Farm

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	1.6	1.7	1.4	1.9
20cm	2.3	2.1	2.0	2.3
30cm	2.1	3.3	3.2	3.3
40cm	4.5	4.2	4.3	4.2
50cm	6.1	6.2	6.4	6.2
60cm	6.1	6.0	5.9	5.5
70cm	4.2	4.0	4.0	3.7
80cm	3.0	2.9	2.8	2.6
Total	29.8	30.5	30.0	29.8
ΔS	29.8	-0.7	0.5	0.2
P	21.0	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	50.8	17.7	0.5	20.2
E/day	1.3	0.3	0.0	0.3
ΣE	50.8	68.5	69.1	89.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 23: The effect of a once-off MP treatment on the soil water balance of a LWCW cropping system during the 2014 fallow season at Langgewens Research Farm

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	0.8	0.7	0.6	0.7
20cm	2.5	2.5	2.2	3.5
30cm	2.1	2.4	2.4	2.5
40cm	1.5	1.7	1.6	1.7
50cm	3.2	5.8	5.8	5.1
60cm	6.2	8.0	7.9	7.5
70cm	4.9	5.4	5.5	5.4
80cm	4.7	5.0	5.0	4.8
Total	26.0	31.5	31.0	31.1
ΔS	26.0	-5.5	0.5	-0.1
P	21.0	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	47.0	12.9	0.5	19.9
E/day	1.2	0.2	0.0	0.3
ΣE	47.0	59.9	60.4	80.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 24: The effect of a once-off DT treatment on the soil water balance of a LWCW cropping system during the 2014 fallow season at Langgewens Research Farm

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	0.5	0.7	0.4	0.5
20cm	2.7	3.1	2.6	2.7
30cm	0.6	1.5	0.3	0.4
40cm	1.2	1.2	0.1	0.3
50cm	1.8	2.2	1.6	2.1
60cm	2.5	4.1	4.1	4.5
70cm	3.2	5.1	5.1	5.2
80cm	2.2	3.3	3.3	3.2
Total	14.7	21.1	17.5	18.9
ΔS	14.7	-6.4	3.6	-1.5
P	21	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	35.7	12.0	3.6	18.5
E/day	0.9	0.2	0.2	0.3
ΣE	35.7	47.7	51.3	69.8

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 25: The effect of a once-off NT treatment on the soil water balance of a WLWC cropping system during the 2014 fallow season at Langgewens Research Farm.

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	0.4	1.4	1.1	1.5
20cm	1.7	3.1	2.9	3.2
30cm	1.6	1.7	1.7	1.6
40cm	1.4	2.3	2.2	2.4
50cm	2.7	4.3	4.4	4.4
60cm	5.2	6.6	6.6	6.5
70cm	7.8	7.9	8.4	8.2
80cm	12.0	10.1	10.5	10.1
Total	32.8	37.4	37.8	38.0
ΔS	32.8	-4.6	-0.4	-0.2
P	21.0	18.4	0.0	20.0
U	0.0	0.0	0.4	0.0
E	53.8	13.8	0.0	19.8
E/day	1.4	0.2	0.0	0.3
ΣE	53.8	67.6	67.6	87.4

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 26: The effect of a once-off MP treatment on the soil water balance of a WLWC cropping system during the 2014 fallow season at Langgewens Research Farm.

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	2.0	0.7	0.5	0.7
20cm	5.3	3.7	3.2	3.7
30cm	1.2	1.4	1.4	1.4
40cm	2.9	1.6	1.6	1.8
50cm	7.0	5.4	5.5	5.4
60cm	8.3	7.1	7.1	6.7
70cm	8.9	7.0	7.0	6.9
80cm	8.3	7.4	7.4	6.3
Total	43.8	34.3	33.6	32.8
ΔS	43.8	9.5	0.7	0.8
P	21.0	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	64.8	27.9	0.7	20.8
E/day	1.7	0.4	0.0	0.3
ΣE	64.8	92.7	93.4	114.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 27: The effect of a once-off DT treatment on the soil water balance of a WLWC cropping system during the 2014 fallow season at Langgewens Research Farm.

Date Depth	04-12-14	11-02-15	05-03-15	11-05-15
10cm	1.0	0.3	0.2	0.3
20cm	1.3	0.8	0.7	0.8
30cm	0.3	0.3	0.3	1.2
40cm	3.0	2.4	2.3	2.5
50cm	5.1	5.1	5.0	6.1
60cm	7.6	9.9	9.9	9.8
70cm	9.3	12.4	12.3	12.2
80cm	7.9	10.9	10.9	10.4
Total	35.5	42.1	41.8	43.4
ΔS	35.5	-6.5	0.2	-1.6
P	21.0	18.4	0.0	20.0
U	0.0	0.0	0.0	0.0
E	56.5	11.9	0.2	18.4
E/day	1.5	0.2	0.0	0.3
ΣE	56.5	68.4	68.6	87.0

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; E= Evaporation (mm); E/day=Evaporation/day (mm); ΣE= cumulative Evaporation (mm), negative ΔW values indicate an increase in SWC

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Appendix D: Soil water balance sheets of different crop rotation systems under different tillage treatments throughout the 2015 growing season at Langgewens

Table 28: The effect of a once-off NT treatment on the soil water balance of a WMcWMc cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	1.10	1.41	3.98	3.82	5.78	7.14	4.61	4.92	7.81	3.31	6.88	8.10	5.68	4.44	3.87	2.61	2.53	2.08	1.56	1.40	1.40	1.10
20cm	2.20	2.46	7.20	6.45	10.45	11.77	8.20	8.49	10.58	10.33	10.44	10.30	8.92	7.14	6.56	4.61	4.41	4.10	3.08	3.30	3.43	3.32
30cm	1.90	1.33	5.20	4.47	6.96	7.47	5.46	5.42	6.41	10.00	6.96	6.52	6.32	5.51	5.03	3.68	3.51	3.17	2.45	2.77	2.75	2.78
40cm	1.80	1.51	3.46	3.37	5.13	5.14	4.21	3.96	5.52	5.07	5.89	5.92	5.68	5.29	5.25	4.30	4.07	3.62	3.23	2.93	2.92	2.92
50cm	4.30	3.93	6.64	6.13	8.32	7.99	7.29	7.14	8.76	5.19	9.69	9.83	9.49	8.88	8.77	7.60	7.27	6.62	5.48	5.32	5.48	5.49
60cm	5.00	4.36	5.24	4.98	5.93	5.54	5.53	5.56	6.48	2.85	7.54	7.73	7.90	7.86	7.95	7.16	6.97	6.28	6.27	5.33	5.19	5.19
70cm	5.50	4.85	5.26	4.94	5.98	5.38	5.52	5.45	6.78	15.73	8.33	8.57	8.81	8.78	9.19	8.64	8.46	7.71	8.52	6.24	6.40	6.27
80cm	7.60	8.29	8.68	8.06	10.82	11.19	11.07	9.20	10.97	14.28	13.59	13.99	14.38	14.48	14.97	14.49	14.51	13.54	13.14	11.76	11.60	11.45
0-40cm	7.00 a	6.71 a	19.84 a	18.10 a	28.3 a2	31.51 a	22.48 a	22.80 a	30.32 a	28.70 a	30.17 a	30.84 a	26.59 a	22.39 a	20.71 a	15.20 a	14.52 a	12.97 a	10.32 a	10.40 a	10.50 a	10.12 a
50-80cm	22.40 b	21.43 b	25.82 a	24.12 a	31.06 a	30.09 a	29.41 a	27.34 a	32.98 a	38.05 b	39.15 b	40.12 b	40.58 b	40.01 b	40.87 b	37.89 b	37.22 b	34.14 b	33.41 b	28.65 b	28.67 b	28.39 b
Total	29.40	28.14	45.66	42.22	59.38	61.60	51.89	50.14	63.30	66.75	69.32	70.96	67.17	62.40	61.58	53.09	51.74	47.10	43.73	39.05	39.16	38.50
ΔS		1.3	-17.5	3.4	-17.2	-2.2	9.7	1.7	-13.2	-3.4	-2.6	-1.6	3.8	4.8	0.8	8.5	1.35	4.64	3.38	4.67	-0.11	0.66
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
ET		11.9	0.0	27.8	5.0	6.2	11.7	9.5	19.0	8.0	1.6	8.0	4.6	9.6	7.2	12.5	6.1	6.8	4.0	7.5	0.0	0.7
ET/day		1.2	0.0	4.6	0.5	0.9	1.3	0.9	1.9	1.0	0.3	1.0	0.8	1.4	1.0	1.0	0.8	0.9	0.7	0.9	0.0	0.1
∑ ET		11.9	11.9	39.7	44.7	50.9	62.6	72.2	91.2	99.2	100.8	108.8	113.4	122.9	130.1	142.6	148.8	155.6	159.6	167.1	167.1	167.7

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 29: The effect of a once-off MP treatment on the soil water balance of a WMcWMc cropping system during the 2015 growing season at Langgewens Research Farm.

Date / Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	1.50	3.29	9.57	6.66	10.43	11.02	6.87	7.97	11.28	6.17	11.12	13.07	11.19	10.16	9.16	4.54	4.86	4.37	3.13	3.25	2.86	2.47
20cm	3.30	3.05	7.90	8.59	8.02	8.85	6.12	6.57	8.64	9.07	8.39	9.41	8.03	7.49	7.37	3.73	3.80	3.47	3.07	2.96	2.99	2.90
30cm	4.70	4.17	10.14	9.30	10.09	10.94	7.96	8.33	10.49	11.07	11.12	11.74	10.72	9.62	8.82	5.30	5.08	4.56	4.11	3.97	4.10	4.12
40cm	4.40	4.08	9.31	8.36	9.91	12.35	9.53	9.76	12.78	11.28	13.44	13.84	13.09	12.33	11.84	8.27	6.98	6.09	5.51	5.21	5.41	5.51
50cm	5.70	5.11	8.94	6.44	10.18	9.94	8.65	8.68	13.77	11.71	18.08	15.25	14.71	14.71	14.88	11.61	11.32	9.60	9.00	8.24	8.50	8.38
60cm	8.60	7.41	11.75	14.66	11.36	10.88	10.50	10.53	16.72	11.74	19.28	18.40	15.10	18.28	18.80	14.42	17.09	15.16	14.22	12.46	12.29	12.04
70cm	10.60	9.45	14.30	17.72	13.53	12.86	12.53	12.37	18.13	20.29	20.88	20.87	15.57	20.87	21.43	16.59	19.96	18.29	16.92	14.80	14.60	14.27
80cm	11.04	9.87	14.06	16.98	13.47	12.29	12.29	12.15	21.70	26.00	27.05	27.04	27.35	27.03	27.63	23.63	25.92	23.94	22.04	19.57	19.06	18.52
0-40cm	13.90 a	14.59 a	36.91 a	32.90 a	38.45 a	43.16 a	30.48 a	32.64 a	43.20 a	37.59 a	44.06 a	48.05 a	43.04 a	39.59 a	37.18 a	21.85 a	20.72 a	18.49 a	15.81 a	15.39 a	15.36 a	15.01 a
50-80cm	35.94 b	31.84 b	49.05 b	55.81 b	48.53 b	45.98 a	43.97 b	43.73 b	70.31 b	69.74 b	85.29 b	81.56 b	72.73 b	80.89 b	82.74 b	66.25 b	74.29 b	66.99 b	62.18 b	55.06 b	54.46 b	53.21 b
Total	49.84	46.43	85.96	88.71	86.98	89.14	74.44	76.36	113.51	107.33	129.35	129.61	115.76	120.48	119.93	88.10	95.01	85.49	78.00	70.45	69.81	68.21
ΔS		3.4	-39.5	-2.8	1.7	-2.2	14.7	-1.9	-37.1	6.2	-22.0	-0.3	13.8	-4.7	0.6	31.8	-6.9	9.53	7.49	7.54	0.64	1.60
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	29.7	0.0	0.0	0.0	0.0	0.0	4.9	0.0	17.8	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0
ET		14.0	0.0	21.6	23.9	6.2	16.7	5.9	0.0	17.6	0.0	9.3	14.6	0.1	7.0	35.8	0.0	11.7	8.1	10.3	0.6	1.6
ET/day		1.4	0.0	3.6	2.4	0.9	1.9	0.6	0.0	2.2	0.0	1.2	2.4	0.0	1.0	3.0	0.0	1.5	1.3	1.2	0.1	0.3
∑ ET		14.0	14.0	35.7	59.6	65.8	82.5	88.4	88.4	106.0	106.0	115.3	130.0	130.1	137.0	172.8	172.8	184.6	192.7	203.0	203.6	205.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 30: The effect of a once-off DT treatment on the soil water balance of a WMcWMc cropping system during the 2015 growing season at Langgewens Research Farm.

Date / Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	1.50	1.50	4.07	3.59	6.60	7.74	4.67	5.41	7.77	7.79	7.33	8.42	6.17	4.35	4.67	2.92	2.75	2.52	1.82	1.79	1.77	1.51
20cm	1.60	1.12	2.98	2.55	6.27	6.88	4.02	4.25	5.69	10.43	5.60	5.04	4.40	3.26	3.42	2.34	2.43	2.14	1.90	1.89	1.74	1.66
30cm	2.80	2.15	5.46	4.50	9.76	10.60	6.90	6.79	8.81	11.93	8.90	8.28	7.29	5.79	5.31	4.16	4.00	3.78	3.20	3.09	3.31	3.28
40cm	3.30	2.69	4.51	3.81	6.51	8.15	5.58	5.51	7.62	9.54	8.71	8.69	7.86	6.84	6.60	4.65	4.50	4.13	3.70	3.38	3.58	3.51
50cm	5.60	3.92	5.76	4.94	7.70	9.18	6.43	6.59	10.28	11.58	11.74	11.84	11.25	10.41	9.37	7.25	6.73	6.07	5.39	5.35	5.38	5.33
60cm	7.10	4.52	6.24	5.45	7.85	7.09	6.54	6.64	9.58	9.61	12.47	12.60	12.73	12.56	13.07	10.24	9.14	8.20	7.46	7.13	7.09	7.03
70cm	6.70	3.83	4.57	4.22	10.51	7.28	7.00	7.15	9.66	22.05	14.17	14.33	10.72	14.20	13.15	12.81	11.43	10.22	9.44	8.63	8.46	8.27
80cm	5.80	7.31	7.29	6.70	8.83	6.89	6.84	6.83	7.81	17.99	11.13	11.60	11.43	11.87	12.96	10.97	10.63	9.72	8.91	8.43	8.37	8.09
0-40cm	9.20 a	7.45 a	17.02 a	14.45 a	29.14 a	33.38 a	21.17 a	21.96 a	29.89 a	39.69 a	30.54 a	30.42 a	25.72 a	20.24 a	20.00 a	14.07 a	13.67 a	12.57 a	10.62 a	10.15 a	10.41 a	9.95 a
50-80cm	25.20 b	19.58 b	23.86 b	21.30 b	34.89 a	30.45 a	26.81 a	27.20 a	37.32 a	61.24 b	49.52 b	50.37 b	46.13 b	49.04 b	48.54 b	41.26 b	37.93 b	34.21 b	31.20 b	29.55 b	29.30 b	28.72 b
Total	34.40	27.04	40.88	35.74	64.03	63.83	47.98	49.16	67.21	100.93	80.05	80.79	71.85	69.28	68.54	55.33	51.60	46.78	41.82	39.70	39.71	38.68
ΔS		7.4	-13.8	5.1	-28.3	0.2	15.8	-1.2	-18.0	-33.7	20.9	-0.7	8.9	2.6	0.7	13.2	3.73	4.82	4.96	2.12	-0.01	1.03
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	4.0	0.0	6.1	0.0	0.0	0.0	0.0	22.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		18.0	0.0	29.5	0.0	8.6	17.8	6.6	14.2	0.0	25.1	8.9	9.7	7.4	7.1	17.2	8.5	7.0	5.6	4.9	0.0	1.0
ET/day		1.8	0.0	4.9	0.0	1.2	2.0	0.7	1.4	0.0	4.5	1.1	1.6	1.1	1.0	1.4	1.1	0.9	0.9	0.6	0.0	0.2
∑ ET		18.0	18.0	47.5	47.5	56.1	73.9	80.6	94.7	94.7	119.8	128.7	138.4	145.8	152.9	170.1	178.6	185.7	191.2	196.1	196.1	197.2

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 31: The effect of a once-off NT treatment on the soil water balance of a CWLW cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	1.50	0.17	0.49	0.37	0.73	0.96	0.53	0.47	0.79	2.70	0.74	1.04	0.76	0.85	0.68	0.48	0.49	0.41	0.25	0.23	0.21	0.23
20cm	3.20	0.16	1.23	0.99	2.39	2.69	1.52	1.75	3.04	6.68	2.77	2.81	2.42	1.22	1.62	0.81	1.05	0.92	0.72	0.71	0.77	0.73
30cm	1.60	0.45	1.31	0.97	2.17	2.24	1.42	1.43	2.98	8.04	4.40	4.34	3.81	2.76	2.63	1.56	1.72	1.56	1.26	1.19	1.18	1.24
40cm	2.40	1.53	6.82	5.13	9.48	9.65	7.72	7.30	8.39	6.08	8.81	8.35	8.29	6.38	6.50	4.52	4.65	4.32	3.84	3.69	3.72	3.75
50cm	4.40	2.51	3.35	2.82	6.03	4.71	3.67	3.65	6.24	5.12	7.26	6.70	6.90	6.17	6.03	4.24	3.92	3.71	3.24	3.12	3.34	3.37
60cm	6.50	3.62	4.21	3.49	17.44	11.76	8.31	8.54	10.32	6.03	9.83	9.09	9.33	8.47	10.00	6.90	6.55	6.03	5.37	4.57	4.75	4.86
70cm	8.20	6.95	8.58	7.18	17.45	12.81	10.54	11.08	14.24	18.76	15.45	15.14	15.71	14.84	15.02	10.93	10.55	9.68	8.70	8.29	8.51	8.54
80cm	10.10	9.25	15.76	12.76	22.08	19.01	15.79	16.28	19.75	16.39	21.09	20.61	21.22	20.56	21.09	17.07	15.97	14.60	13.29	12.83	13.08	13.03
0-40cm	8.70 a	2.32 a	9.86 a	7.46 a	14.77 a	15.53 a	11.20 a	10.95 a	15.20 a	23.50 a	16.72 a	16.55 a	15.28 a	11.21 a	11.43 a	7.38 a	7.91 a	7.20 a	6.06 a	5.82 a	5.89 a	5.94 a
50-80cm	29.20 b	22.33 b	31.90 b	26.25 b	63.01 b	48.28 b	38.31 b	39.55 b	50.55 b	46.30 b	53.63 b	51.53 b	53.16 b	50.04 b	52.15 b	39.13 b	36.99 b	34.03 b	30.61 b	28.80 b	29.67 b	29.80 b
Total	37.90	24.65	41.76	33.71	77.77	63.82	49.52	50.50	65.75	69.81	70.35	68.08	68.44	61.26	63.58	46.52	44.90	41.23	36.67	34.62	35.56	35.74
ΔS		13.2	-17.1	8.0	-44.1	14.0	14.3	-1.0	-15.2	-4.1	-0.5	2.3	-0.4	7.2	-2.3	17.1	1.6	3.67	4.57	2.05	-0.94	-0.18
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	7.3	0.0	21.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.2
ET		23.8	0.0	32.4	0.0	22.4	16.3	6.8	17.0	7.3	3.7	11.9	0.4	12.0	4.1	21.1	6.4	5.9	5.2	4.8	0.0	0.0
ET/day		2.4	0.0	5.4	0.0	3.2	1.8	0.7	1.7	0.9	0.7	1.5	0.1	1.7	0.6	1.8	0.8	0.7	0.9	0.6	0.0	0.0
∑ ET		23.8	23.8	56.3	56.3	78.7	95.0	101.8	118.7	126.1	129.7	141.6	142.0	154.0	158.1	179.2	185.6	191.4	196.6	201.5	201.5	201.5

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 32: The effect of a once-off MP treatment on the soil water balance of a CWLW cropping system during the 2015 growing season at Langgewens Research Farm.

Date / Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	0.70	1.73	5.50	3.25	5.11	5.34	3.12	3.15	4.61	2.14	4.61	5.22	3.59	2.63	2.50	1.72	1.96	1.69	1.38	1.35	1.06	1.14
20cm	3.70	0.77	2.19	1.64	9.84	9.23	6.77	7.06	8.48	4.97	8.41	8.65	7.62	5.83	5.28	3.79	3.73	3.48	2.88	2.81	3.14	3.11
30cm	1.40	1.53	3.62	3.85	6.36	6.96	4.63	4.36	7.43	15.38	12.29	11.82	10.82	7.54	7.22	4.80	4.85	4.48	3.90	4.28	3.87	3.41
40cm	1.80	1.88	3.89	2.96	14.63	10.88	7.90	9.55	11.80	14.60	11.55	11.55	11.15	9.24	8.82	6.26	6.29	5.92	5.30	5.26	5.21	5.27
50cm	5.40	2.26	3.75	6.89	23.57	21.42	15.10	15.39	18.42	15.32	18.08	17.62	17.64	16.28	15.90	12.33	11.99	11.24	9.88	9.42	10.04	10.11
60cm	6.70	2.95	3.63	9.01	18.32	20.63	14.68	16.07	19.18	14.41	19.09	19.68	19.50	18.24	18.35	14.37	13.68	12.65	11.56	11.04	11.47	11.48
70cm	6.90	2.70	2.78	8.99	19.33	23.46	17.12	17.50	19.57	25.36	20.14	20.72	20.65	19.85	20.25	16.76	15.65	14.45	13.63	13.34	13.19	13.01
80cm	6.30	5.08	2.45	9.19	21.97	22.48	16.52	16.88	19.11	23.78	19.66	20.30	20.32	19.92	20.42	17.91	16.86	15.51	14.49	14.03	14.23	13.92
0-40cm	7.60 a	5.91 a	15.20 a	11.70 a	35.94 a	32.42 a	22.42 a	24.12 a	32.32 a	37.09 a	36.87 a	37.24 a	33.19 a	25.25 a	23.82 a	16.56 a	16.84 a	15.57 a	13.47 a	13.71 a	13.29 a	12.93 a
50-80cm	25.30 b	12.99 b	12.61 b	34.08 b	83.19 b	87.98 b	63.42 b	65.84 b	76.27 b	78.87 b	76.96 b	78.31 b	78.10 b	74.29 b	74.91 b	61.38 b	58.18 b	53.85 b	49.55 b	47.83 b	48.93 b	48.53 b
Total	32.90	18.91	27.81	45.78	119.14	120.40	85.84	89.97	108.59	115.96	113.83	115.56	111.29	99.54	98.73	77.94	75.02	69.42	63.02	61.55	62.22	61.45
ΔS		14.0	-8.9	-18.0	-73.4	-1.3	34.6	-4.1	-18.6	-7.4	2.1	-1.7	4.3	11.8	0.8	20.8	2.9	5.6	6.4	1.5	-0.7	0.8
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	0.0	0.0	51.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0
ET		24.6	0.9	6.4	0.0	7.1	36.6	3.7	13.6	4.0	6.3	7.9	5.1	16.6	7.2	24.8	7.7	7.8	7.0	4.3	0.0	0.8
ET/day		2.5	0.1	1.1	0.0	1.0	4.1	0.4	1.4	0.5	1.1	1.0	0.8	2.4	1.0	2.1	1.0	1.0	1.2	0.5	0.0	0.2
∑ ET		24.6	25.5	31.9	31.9	39.1	75.6	79.3	92.9	96.9	103.2	111.1	116.2	132.7	139.9	164.7	172.4	180.2	187.2	191.5	191.5	192.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 33: The effect of a once-off DT treatment on the soil water balance of a CWLW cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	0.30	0.35	1.83	1.20	2.42	2.51	1.20	1.38	1.27	4.25	2.03	2.46	1.59	1.04	0.94	0.57	0.83	0.67	0.38	0.38	0.37	0.37
20cm	0.80	0.39	2.20	1.80	3.28	3.51	2.40	2.37	3.42	8.36	3.56	3.47	2.82	2.01	1.90	1.28	1.38	1.24	1.01	0.97	0.97	1.00
30cm	1.20	0.74	2.91	2.42	3.99	4.18	2.75	2.63	3.52	8.64	3.90	3.96	3.11	2.31	2.26	1.59	1.68	1.50	1.23	1.26	1.20	1.30
40cm	2.50	2.14	3.06	2.71	4.33	4.25	3.32	3.24	4.59	4.27	5.08	5.17	4.96	4.52	4.41	3.06	3.14	2.88	2.52	2.53	2.52	2.58
50cm	6.10	2.45	2.47	2.39	10.63	9.13	7.88	7.16	9.70	6.49	11.61	11.10	11.46	10.52	10.09	7.88	7.67	7.03	6.49	6.38	6.58	6.74
60cm	9.80	3.96	8.07	7.39	11.08	9.20	8.85	8.80	13.42	11.21	15.92	15.71	16.33	15.64	15.09	12.76	12.02	11.44	10.57	10.42	10.58	10.63
70cm	12.20	10.95	9.12	8.75	16.20	14.63	14.40	14.46	14.81	22.71	17.16	17.12	17.68	17.45	17.33	14.92	14.17	13.26	12.23	12.07	12.14	12.20
80cm	10.40	12.99	11.28	11.07	18.29	16.57	16.51	16.24	16.37	20.15	18.67	18.72	19.27	19.31	19.78	18.16	17.89	16.74	15.55	15.11	15.07	14.94
0-40cm	4.80 a	3.61 a	10.00 a	8.12 a	14.02 a	14.44 a	9.66 a	9.62 a	12.80 a	25.52 a	14.58 a	15.06 a	12.47 a	9.87 a	9.50 a	6.49 a	7.03 a	6.29 a	5.14 a	5.14 a	5.06 a	5.24 a
50-80cm	38.50 b	30.35 b	30.95 b	29.60 b	56.20 b	49.54 b	47.62 b	46.67 b	54.30 b	60.57 b	63.35 b	62.64 b	64.74 b	62.93 b	62.29 b	53.71 b	51.75 b	48.46 b	44.84 b	43.97 b	44.37 b	44.52 b
Total	43.30	33.96	40.95	37.72	70.22	63.98	57.29	56.28	67.09	86.09	77.93	77.70	77.21	72.79	71.80	60.20	58.78	54.75	49.98	49.11	49.43	49.76
ΔS		9.3	-7.0	3.2	-32.5	6.2	6.7	1.0	-10.8	-19.0	8.2	0.2	0.5	4.4	1.0	11.6	1.4	4.0	4.8	0.9	-0.3	-0.3
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	0.0	0.0	10.3	0.0	0.0	0.0	0.0	7.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
ET		19.9	2.8	27.6	0.0	14.6	8.7	8.8	21.4	0.0	12.4	9.8	1.3	9.2	7.4	15.6	6.2	6.2	5.4	3.7	0.0	0.0
ET/day		2.0	0.3	4.6	0.0	2.1	1.0	0.9	2.1	0.0	2.2	1.2	0.2	1.3	1.1	1.3	0.8	0.8	0.9	0.4	0.0	0.0
∑ ET		19.9	22.8	50.4	50.4	65.0	73.7	82.5	103.9	103.9	116.3	126.1	127.4	136.6	144.0	159.6	165.8	172.0	177.4	181.1	181.1	181.1

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 34: The effect of a once-off NT treatment on the soil water balance of a WLWC cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	1.90	0.36	1.53	1.51	2.54	3.07	1.88	1.76	2.99	3.61	2.78	3.16	2.39	2.10	2.02	1.59	1.43	1.22	0.94	0.91	0.83	0.79
20cm	2.30	0.21	0.96	0.94	2.22	2.46	1.60	1.97	2.73	8.42	2.50	2.47	1.90	1.71	1.76	1.47	1.31	1.08	0.90	0.85	0.83	0.79
30cm	3.30	0.85	3.08	2.66	6.12	6.31	4.30	5.16	5.42	10.71	5.69	5.71	4.26	3.59	3.56	2.79	2.49	2.18	1.85	1.86	1.83	1.73
40cm	4.20	2.32	3.90	2.95	6.55	7.24	5.87	5.97	8.40	6.64	9.90	10.01	8.59	7.31	6.92	5.63	5.22	4.83	4.05	4.12	3.96	3.95
50cm	6.20	1.79	4.87	3.69	5.43	5.79	4.29	2.80	5.68	5.07	6.52	6.88	5.96	5.14	4.99	4.22	3.83	3.73	3.27	3.06	3.10	2.97
60cm	5.50	3.90	7.09	3.98	6.86	5.85	4.39	2.53	6.18	3.79	7.23	7.83	7.27	6.47	6.15	4.86	4.20	3.83	3.59	3.32	3.26	3.16
70cm	3.70	4.73	7.78	4.55	13.40	8.03	6.06	5.94	8.20	19.95	9.69	10.33	10.22	9.53	8.95	7.15	6.39	6.11	5.58	5.40	5.39	5.19
80cm	2.60	6.59	10.80	7.47	14.00	11.85	8.48	7.09	9.93	16.79	12.20	13.09	13.06	12.71	12.14	10.28	9.25	8.78	8.12	7.85	7.78	7.73
0-40cm	11.70 a	3.75 a	9.47 a	8.06 a	17.42 a	19.08 a	13.65 a	14.87 a	19.54 a	29.38 a	20.87 a	21.35 a	17.15 a	14.71 a	14.25 a	11.48 a	10.45 a	9.30 a	7.74 a	7.74 a	7.45 a	7.25 a
50-80cm	18.00 b	17.01 b	30.54 b	19.69 b	39.68 b	31.52 b	23.22 b	18.35 b	29.99 b	45.60 b	35.64 b	38.12 b	36.50 b	33.86 b	32.23 b	26.51 b	23.67 b	22.44 b	20.56 b	19.63 b	19.54 b	19.05 b
Total	29.70	20.76	40.02	27.75	57.10	50.60	36.87	33.22	49.53	74.98	56.50	59.47	53.65	48.56	46.48	38.00	34.11	31.74	28.30	27.37	26.99	26.30
ΔS		8.9	-19.3	12.3	-29.4	6.5	13.7	3.6	-16.3	-25.4	18.5	-3.0	5.8	5.1	2.1	8.5	3.88	2.37	3.44	0.93	0.39	0.69
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	9.5	0.0	7.2	0.0	0.0	0.0	0.0	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		19.5	0.0	36.7	0.0	14.9	15.7	11.4	15.9	0.0	22.7	6.6	6.6	9.9	8.5	12.5	8.7	4.6	4.0	3.7	0.4	0.7
ET/day		2.0	0.0	6.1	0.0	2.1	1.8	1.1	1.6	0.0	4.1	0.8	1.1	1.4	1.2	1.0	1.1	0.6	0.7	0.4	0.1	0.1
∑ ET		19.5	19.5	56.2	56.2	71.1	86.8	98.3	114.2	114.2	136.9	143.5	150.1	160.0	168.5	181.0	189.6	194.2	198.3	202.0	202.4	203.1

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 35: The effect of a once-off MP treatment on the soil water balance of a WLWC cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	0.74	0.22	1.17	1.00	3.15	5.04	2.88	3.67	3.35	2.93	3.24	3.24	2.20	1.86	1.98	1.51	1.43	1.21	0.96	0.96	0.81	0.79
20cm	3.50	0.18	1.39	1.55	2.54	3.47	2.22	2.50	4.33	6.68	3.90	3.54	2.85	2.24	2.28	1.89	1.78	1.53	1.26	1.31	1.19	1.20
30cm	2.50	0.31	1.76	1.74	3.59	5.39	3.02	3.33	6.71	6.82	7.07	6.13	5.10	4.36	4.16	3.23	3.06	2.80	2.18	2.25	2.23	2.22
40cm	1.70	0.81	4.48	1.55	3.06	4.05	3.01	3.06	7.86	3.45	7.64	7.42	6.79	5.67	5.35	4.15	4.00	3.65	3.34	3.17	3.15	2.96
50cm	5.10	2.08	4.32	1.35	2.77	3.25	2.62	2.73	6.48	3.92	6.76	6.94	6.79	6.30	5.69	4.74	4.47	4.04	3.74	3.57	3.37	3.24
60cm	7.50	1.30	2.02	1.01	13.45	7.83	5.50	5.71	9.65	2.10	10.22	10.50	10.48	10.16	9.23	7.49	6.85	6.16	5.64	5.43	5.26	5.12
70cm	5.40	1.15	4.80	4.64	12.96	9.67	5.75	6.03	11.30	14.03	12.89	13.39	13.11	13.03	11.88	9.12	8.06	7.09	6.56	6.20	5.96	5.95
80cm	4.80	9.80	13.15	14.86	18.33	18.34	11.74	11.97	17.65	17.93	20.47	20.69	20.82	21.38	21.12	17.40	15.36	13.90	12.53	11.93	11.75	11.62
0-40cm	8.44 a	1.52 a	8.79 a	5.85 a	12.34 a	17.95 a	11.12 a	12.55 a	22.26 a	19.89 a	21.85 a	20.33 a	16.94 a	14.13 a	13.76 a	10.78 a	10.27 a	9.19 a	7.74 a	7.69 a	7.38 a	7.18 a
50-80cm	22.80 b	14.33 b	24.30 b	21.87 b	47.51 b	39.09 b	25.60 b	26.44 b	45.09 b	37.98 b	50.34 b	51.52 b	51.20 b	50.87 b	47.93 b	38.76 b	34.75 b	31.19 b	28.47 b	27.12 b	26.34 b	25.93 b
Total	31.24	15.85	33.09	27.71	59.85	57.04	36.72	38.99	67.34	57.87	72.19	71.85	68.14	65.00	61.69	49.54	45.02	40.39	36.21	34.81	33.72	33.10
ΔS		15.4	-17.2	5.4	-32.1	2.8	20.3	-2.3	-28.4	9.5	-14.3	0.3	3.7	3.1	3.3	12.2	4.5	4.6	4.2	1.4	1.1	0.6
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	7.4	0.0	9.9	0.0	0.0	0.0	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ET		26.0	0.0	29.8	0.0	11.2	22.3	5.5	3.8	20.9	0.0	9.9	4.5	7.9	9.7	16.2	9.3	6.8	4.8	4.2	1.1	0.6
ET/day		2.6	0.0	4.9	0.0	1.6	2.5	0.6	0.4	2.7	0.0	1.2	0.8	1.1	1.4	1.3	1.2	0.9	0.8	0.5	0.2	0.1
∑ ET		26.0	26.0	55.8	55.8	67.0	89.3	94.8	98.7	119.5	119.5	129.5	134.0	141.9	151.6	167.8	177.1	184.0	188.7	192.9	194.0	194.6

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Table 36: The effect of a once-off DT treatment on the soil water balance of a WLWC cropping system during the 2015 growing season at Langgewens Research Farm.

Date Depth	12-05-15	22-05-15	01-06-15	07-06-15	17-06-15	24-06-15	03-07-15	13-07-15	23-07-15	31-07-15	06-08-15	14-08-15	20-08-15	27-08-15	03-09-15	15-09-15	23-09-15	01-10-15	07-10-15	15-10-15	22-10-15	27-10-15
10cm	0.50	0.04	1.44	0.14	0.25	0.46	0.21	0.32	0.49	2.43	0.47	0.75	0.38	0.36	0.48	0.34	0.58	0.33	0.23	0.17	0.18	0.15
20cm	2.70	0.03	1.80	0.09	0.14	0.16	0.10	0.11	0.30	6.49	0.34	0.38	0.23	0.24	0.35	0.28	0.32	0.31	0.25	0.21	0.21	0.20
30cm	0.40	0.35	3.58	1.23	2.60	2.48	1.59	1.66	1.81	6.49	1.63	1.56	1.57	1.11	1.10	0.99	1.19	0.82	0.80	0.72	0.77	0.80
40cm	0.30	0.15	1.85	1.37	3.34	3.56	2.26	2.35	2.82	2.80	3.01	2.80	2.28	1.61	1.56	1.21	1.18	1.01	0.85	0.81	0.82	0.82
50cm	2.10	0.85	5.83	3.95	13.13	11.96	7.97	8.31	8.81	3.34	10.87	10.25	9.64	8.40	7.69	6.37	5.85	5.27	4.21	4.70	4.78	4.67
60cm	4.50	2.44	8.15	4.89	14.62	7.33	4.97	5.19	6.35	1.86	7.85	7.58	7.15	6.39	6.22	4.77	4.33	3.82	3.67	3.23	3.37	3.24
70cm	5.20	3.27	11.85	3.61	13.96	8.31	6.55	7.17	8.03	13.43	9.43	9.45	8.50	9.02	8.82	8.07	7.77	7.14	5.22	6.38	6.48	6.38
80cm	3.20	3.43	13.54	8.63	16.23	12.81	12.02	12.68	13.58	11.69	15.86	16.08	15.97	15.35	15.05	13.15	13.04	12.57	11.53	11.67	11.73	11.58
0-40cm	3.90 a	0.57 a	8.66 a	2.83 a	6.32 a	6.66 a	4.16 a	4.44 a	5.42 a	18.21 a	5.45 a	5.49 a	4.47 a	3.32 a	3.49 a	2.81 a	3.26 a	2.46 a	2.13 a	1.91 a	1.99 a	1.96 a
50-80cm	15.00 b	9.98 b	39.36 b	21.08 b	57.93 b	40.40 b	31.52 b	33.34 b	36.76 b	30.33 b	44.00 b	43.35 b	41.26 b	39.17 b	37.78 b	32.36 b	30.98 b	28.81 b	24.62 b	25.97 b	26.36 b	25.87 b
Total	18.90	10.56	48.03	23.91	64.25	47.07	35.68	37.78	42.18	48.53	49.46	48.84	45.72	42.49	41.28	35.17	34.24	31.27	26.75	27.88	28.34	27.84
ΔS		8.3	-37.5	24.1	-40.3	17.2	11.4	-2.1	-4.4	-6.4	-0.9	0.6	3.1	3.2	1.2	6.1	0.9	3.0	4.52	-1.13	-0.46	0.51
P		10.6	9.8	24.4	22.2	8.4	2.0	7.8	32.2	11.4	4.2	9.6	0.8	4.8	6.4	4.0	4.8	2.2	0.6	2.8	0.0	0.0
U		0.0	27.7	0.0	18.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
ET		18.9	0.0	48.5	0.0	25.6	13.4	5.7	27.8	5.0	3.3	10.2	3.9	8.0	7.6	10.1	5.7	5.2	5.1	1.7	0.0	0.5
ET/day		1.9	0.0	8.1	0.0	3.6	1.5	0.6	2.8	0.6	0.6	1.3	0.7	1.1	1.1	0.8	0.7	0.6	0.9	0.2	0.0	0.1
∑ ET		18.9	18.9	67.5	67.5	93.0	106.4	112.1	139.9	145.0	148.3	158.5	162.4	170.4	178.0	188.1	193.9	199.0	204.2	205.8	205.8	206.3

NT = No-till; MP = Mouldboard plough; DT = Deep tine; ΔS = change in water content (mm); P= precipitation; U = drainage/deep percolation; ET/day=Evapotranspiration/day (mm); ET= Evapotranspiration (mm); ΣET= cumulative Evapotranspiration (mm), negative ΔW values indicate an increase in SWC.

Note 1: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Note 2: Red colored cells indicate the lowest boundary of plant available water

Appendix E: The experimental layout showing the three replications of each crop sequence and tillage operation at Langgewens 2014/2015

WLWC = wheat-lupine-wheat-canola; LWCW = lupine-wheat-canola-wheat; McWMcW = medic-wheat-medic-wheat; CWLW = canola-wheat-lupine-wheat; WWWW = wheat monoculture; WMcWMc = wheat-medic-wheat-medic

Appendix F: Chemical analysis before the application of tillage

Table 37: Ca, Mg, K and Na results of different tillage treatments under different crop rotation systems and depths before tillage at Langgewens Research Farm (2014)

	Tillage treatment	NT				MP				DT			
	Soil depth (mm)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)
McWMcW	0-50	4.36 a	1.49 a	313.25 a	28.00 a	4.20 ab	1.37 ab	273.33 a	27.66 a	3.75 b	1.22 b	269.50 a	44.75 a
	50-100	3.46 ab	1.16 a	215.00 a	21.75 a	3.79 a	1.22 a	205.25 a	25.00 a	3.01 b	0.90 a	176.33 a	32.33 a
	100-200	2.59 ab	0.73 a	164.75 a	20.5 a	2.99 a	0.86 a	154.67 a	25.00 a	2.37 b	0.68 a	141.75 a	30.75 a
	200-300	2.68 a	0.82 a	146.75 a	26.25 b	2.64 a	0.80 a	127.75 a	29.00 ab	2.34 a	0.77 a	120.25 a	36.50 a
	300-400	3.25 a	0.96 a	131.75 a	30.00 b	2.58 a	0.92 a	114.75 a	33.75 ab	2.72 a	1.05 a	117.00 a	40.67 a
WLWC	0-50	3.74 a	1.22 a	196.00 a	28.00 a	3.57 a	1.08 a	232.50 a	39.75 a	3.76 a	1.27 a	203.75 a	43.00 a
	50-100	2.76 a	0.82 a	170.50 a	22.75 a	2.77 a	0.77 a	164.25 a	37.75 a	2.61 a	0.80 a	147.50 a	29.75 a
	100-200	2.16 a	0.60 a	132.25 a	22.75 a	2.04 a	0.57 a	112.75 a	29.75 a	2.04 a	0.62 a	112.00 a	28.50 a
	200-300	2.20 a	0.63 a	114.75 a	24.50 a	1.98 a	0.54 a	101.75 a	29.50 a	2.06 a	0.66 a	104.00 a	32.25 a
	300-400	2.21 a	0.68 a	110.00 a	29.25 a	2.25 a	0.84 a	112.50 a	38.75 a	2.17 a	0.74 a	102.50 a	33.50 a
LWCW	0-50	3.34 a	1.02 a	184.88 a	32.25 ab	3.25 a	1.02 a	182.50 a	27.5 b	3.56 a	1.11 a	166.88 a	39.75 a
	50-100	2.54 a	0.73 a	164.25 a	27.50 a	2.40 a	0.69 a	138.25 a	24.75 a	2.56 a	0.71 a	164.25 a	31.75 a
	100-200	1.81 b	0.51 b	129.50 a	24.50 a	1.90 ab	0.53 ab	118.50 a	23.75 a	2.11 a	0.57 a	129.50 a	27.50 a
	200-300	2.07 a	0.52 a	113.00 a	24.25 a	2.02 a	0.54 a	102.50 a	23.50 a	2.18 a	0.55 a	113.00 a	28.25 a
	300-400	2.19 a	0.65 a	80.52 a	27.25 a	2.18 a	0.58 a	99.75 a	25.25 a	2.38 a	0.70 a	80.52 a	32.75 a

NT = No-till; MP = Mouldboard plough; DT = Deep tine; Ca = calsium content (cmol/kg); Mg = magnesium content (cmol/kg); K = potassium content (mg/kg); Na = sodium content (mg/kg).

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 38: Ca, Mg, K and Na results of different tillage treatments under different crop rotation systems and depths after tillage at Langgewens Research Farm (2015)

	Tillage treatment	**NT**				**MP**				**DT**			
	Soil depth (mm)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)	Ca (cmol/kg)	Mg (cmol/kg)	K (mg/kg)	Na (mg/kg)
McWMcW	0-50	3.49 a	1.15 a	181.25 a	23.25 a	4.22 a	1.39 a	205.75 a	22.00 a	3.34 a	1.03 a	203.75 a	22.00 a
	50-100	3.19 a	1.15 a	147.50 a	28.00 a	3.67 a	1.30 a	152.50 a	22.00 a	3.58 a	1.08 a	146.00 a	24.00 a
	100-200	2.43 a	0.83 a	130.80 a	27.50 a	3.04 a	0.99 a	112.50 a	29.25 a	3.19 a	0.96 a	135.75 a	27.00 a
	200-300	2.34 a	0.72 a	100.80 a	33.50 a	2.61 a	0.87 a	88.00 a	34.50 a	2.56 a	0.81 a	109.25 a	27.25 a
	300-400	2.35 a	1.25 a	100.30 a	74.50 a	2.05 a	1.00 a	86.25 a	40.50 a	2.19 a	0.96 a	99.50 a	51.00 a
WLWC	0-50	3.35 a	1.02 a	202.00 a	24.25 a	3.04 a	0.91 a	182.75 a	37.00 a	3.36 a	0.94 a	198.50 a	32.75 a
	50-100	2.47 a	0.75 a	111.00 a	29.00 a	2.54 a	0.81 a	137.75 a	36.00 a	3.24 a	0.94 a	163.75 a	33.75 a
	100-200	2.17 a	0.67 a	101.75 a	35.75 a	1.92 a	0.55 a	96.00 a	27.50 a	2.37 a	0.63 a	118.75 a	25.25 a
	200-300	2.04 a	0.55 a	77.25 a	32.75 a	1.98 a	0.50 a	93.25 a	29.75 a	1.99 a	0.49 a	91.50 a	26.00 a
	300-400	2.19 a	0.91 a	88.50 a	43.00 a	2.20 a	0.93 a	95.25 a	45.50 a	2.06 a	1.76 a	74.50 a	28.25 a
LWCW	0-50	3.33 a	0.95 a	193.00 a	18.75 b	2.77 a	0.83 a	168.33 a	31.33 a	2.87 a	0.95 a	184.75 a	30.50 a
	50-100	2.72 a	0.77 b	135.00 a	19.25 a	2.85 a	0.92 ab	128.00 a	34.00 a	2.50 a	1.14 a	96.00 a	42.00 a
	100-200	1.95 a	0.47 b	82.00 b	20.25 a	2.51 a	0.74 ab	103.33 a	30.33 a	2.69 a	0.91 a	94.25 ab	45.25 a
	200-300	1.94 b	0.51 a	73.25 a	33.75 a	2.50 a	0.59 a	84.00 a	30.33 a	2.07 ab	0.75 a	78.00 a	48.50 a
	300-400	2.07 a	0.88 a	77.50 a	40.50 a	2.28 a	0.78 a	88.00 a	39.33 a	2.12 a	1.01 a	85.50 a	54.50 a

NT = N0-till; MP = Mouldboard plough; DT = Deep tine; Ca = calsium content (cmol/kg); Mg = magnesium content (cmol/kg); K = potassium content (mg/kg); Na = sodium content (mg/kg).

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 39: Cu, Zn, Mn, B, S results of different tillage treatments under different crop rotation systems and depths before tillage at Langgewens Research Farm (2014)

	Tillage treatment	NT					MP					DT				
	Soil depth (mm)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	S (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	S (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	S (mg/kg)
McWMcW	0-50	1.22 a	14.87 a	151.33 a	0.34 a	6.8 a	1.28 a	7.16 a	156.57 a	0.32 a	5.37 a	1.25 a	5.04 a	149.40 a	0.33 a	8.23 a
	50-100	1.32 a	4.92 a	161.88 a	0.24 a	5.03 a	1.31 a	4.92 a	153.18 a	0.26 a	4.53 a	1.56 a	2.92 a	170.17 a	0.22 a	4.90 a
	100-200	1.42 a	4.00 ab	165.33 a	0.18 a	3.68 a	1.52 a	3.15 a	172.50 a	0.18 a	3.87 a	1.42 a	2.01 b	147.51 a	0.19 a	5.18 a
	200-300	1.52 a	6.13 a	151.24 a	0.21 a	3.93 a	1.56 a	2.04 a	158.00 a	0.22 a	3.83 a	1.51 a	1.68 b	142.18 a	0.21 a	5.25 a
	300-400	1.52 a	11.09 b	134.96 a	0.23 a	3.73 a	1.58 a	2.37 a	159.73 a	0.24 a	4.15 a	1.56 a	1.90 b	129.03 a	0.26 a	6.50 a
WLWC	0-50	1.29 a	9.42 a	170.53 a	0.27 a	6.90 a	1.28 a	7.86 a	151.75 a	0.27a	8.88 a	1.18 a	7.31 a	156.32 a	0.28 a	10.23 a
	50-100	1.27 b	5.91 b	151.28 a	0.20 a	6.05 a	1.39 a	5.32 a	151.04 a	0.22 a	7.65 a	1.36 ab	6.19 b	158.65 a	0.22 a	6.43 a
	100-200	1.40 b	5.19 a	155.39 a	0.18 a	4.88 a	1.47 a	5.72 ab	157.10 a	0.19 a	5.78 a	1.47 a	3.49 b	152.47 a	0.20 a	5.10 a
	200-300	1.44 a	7.36 a	157.94 a	0.19 a	4.93 a	1.55 a	6.97 a	126.82 a	0.21 a	5.03 a	1.54 a	5.30 a	153.25 a	0.21 a	5.15 a
	300-400	1.29 a	12.92 a	112.94 a	0.24 b	5.48 b	1.42 a	9.22 a	105.76 a	0.32 a	7.75 a	1.49 a	14.78 a	105.24 a	0.25 b	5.65 b
LWCW	0-50	1.14 a	5.48 a	160.10 a	0.25 a	13.4 a	1.12 a	5.71 a	155.55 a	0.24 a	9.2 a	1.14 a	6.35 a	153.99 a	0.27 a	15.9 a
	50-100	1.19 a	4.17 a	157.37 a	0.20 b	10.43 a	1.19 a	4.04 a	157.54 a	0.18 b	8.03 a	1.25 a	6.48 a	154.50 a	0.22 a	13.25 a
	100-200	1.29 b	3.39 a	166.67 a	1.17 ab	7.55 a	1.28 b	3.47 a	161.15 a	0.16 b	6.95 a	1.37 a	4.13 a	163.28 a	0.18 a	9.28 a
	200-300	1.41 a	4.50 a	171.05 a	0.18 a	6.63 b	1.40 a	3.98 a	175.29 a	0.18 a	5.58 b	1.48 a	7.09 a	154.27 a	0.21 a	8.83 a
	300-400	1.31 a	7.02 a	131.27 a	0.22 a	5.98 a	1.37 a	9.76 b	140.24 a	0.23 a	5.30 a	1.44 a	12.97 ab	124.26 a	0.24 a	7.53 a

NT = No-till; MP = Mouldboard plough; DT = Deep tine; Cu = copper content (mg/kg); Zn = zinc content (mg/kg); Mn = manganese content (mg/kg); B = boron content (mg/kg); S = sulphur content (mg/kg)

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences

Table 40: Cu, Zn, Mn results of different tillage treatments under different crop rotation systems and depths after tillage at Langgewens Research Farm (2015)

	Tillage treatment	NT			MP			DT		
	Soil depth (mm)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)
McWMcW	0-50	2.01 a	4.60 a	125.95 a	1.84 a	5.39 a	133.10 a	2.32 a	4.01 a	130.27 a
	50-100	2.17 a	4.10 a	129.91 a	2.06 a	3.76 a	136.30 a	2.05 a	3.80 a	128.02 a
	100-200	1.39 b	1.84 a	132.48 a	1.60 a	1.87 a	151.73 a	1.41 ab	2.83 a	144.74 a
	200-300	1.73 a	1.09 a	133.49 a	1.84 a	1.37 a	140.81 a	1.55 a	1.55 a	124.45 a
	300-400	1.64 a	0.50 a	89.20 a	1.50 a	0.71 a	129.46 a	1.50 a	0.70 a	104.91 a
WLWC	0-50	2.28 a	5.00 ab	191.68 a	2.25 a	6.24 a	176.60 a	2.98 a	3.69 b	202.77 a
	50-100	2.56 a	3.10 a	201.15 a	3.22 a	4.67 a	178.67 a	1.79 a	4.55 a	197.13 a
	100-200	2.32 a	2.83 a	208.20 a	1.80 a	1.97 a	185.70 a	1.74 a	2.76 a	198.86 a
	200-300	1.89 a	1.03 a	204.52 a	1.81 a	1.21 a	165.70 a	1.88 a	1.20 a	160.31 a
	300-400	1.72 a	0.57 a	133.69 a	1.75 a	0.50 a	81.01 b	1.48 a	0.73 a	91.14 b
LWCW	0-50	2.42 a	7.45 a	154.40 a	2.71 a	4.05 a	162.00 a	2.06 a	3.22 a	162.83 a
	50-100	2.29 a	3.43 a	164.73 a	2.63 a	3.63 a	171.20 a	2.05 a	2.98 a	161.87 a
	100-200	1.42 a	1.22 a	172.15 a	1.57 a	2.05 a	168.43 a	1.67 a	1.54 a	156.00 a
	200-300	1.58 a	0.88 a	139.30 a	1.90 a	0.89 a	123.37 a	1.77 a	1.36 a	159.94 a
	300-400	1.30 a	0.49 a	116.22 a	1.40 a	0.44 a	98.65 a	1.50 a	0.56 a	128.40 a

NT = No-till; MP = Mouldboard plough; DT = Deep tine; Cu = copper content (mg/kg); Zn = zinc content (mg/kg); Mn = manganese content (mg/kg)

Note: The alphabetic letters denote a statistical difference between treatments and crop rotation systems according to Tukey's Studentized Range Test at α = 0.05. Similar letters indicate a lack of significant differences